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Coastal and Hydraulics Laboratory

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Effects of Lock Sill and Chamber Depths on Transit Time of Shallow Draft Navigation

Stephen T. Maynord

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Preface

The work reported herein was sponsored by Headquarters, U.S. Army Corps of Engineers, as part of the Inland Navigation Research Program under Civil Works Investigation Work Unit 33107, "Depth/Width Requirements for Inland Channels."

The work was performed by members of the staff of the U.S. Army Engineer Research and Development Center (ERDC), Coastal and Hydraulics Laboratory (CHL), during 1998-2000. The study was under the direction of Dr. James R. Houston, former Director, CHL, and Dr. Sandra K. Knight, Chief, Navigation Branch (HN-N), CHL. The study was conducted by Dr. S. T. Maynord, Navigation Branch, HN-N.

At the time of publication of this report, Dr. James R. Houston was Director of ERDC, and COL Robin R. Cababa, EN, was Commander.

1 Introduction

Background

Shallow draft navigation on several of the nation's waterways is maintained by a system of locks and dams. Most of these locks and dams have been in place for many years, and repair or replacement of existing locks or addition of new locks is being considered at several U.S. Army Corps of Engineers projects. As an example, in the Upper Mississippi River-Illinois Waterway (UMR-IWW) System Navigation Study, the principal problem addressed is congestion of commercial traffic at locks upstream of Melvin Price Locks and Dam due to limited lockage capacity and increasing traffic. As evidenced by the Corps' recently initiated research program "Innovations for Navigation Projects," every attempt is being made to reduce lock costs while maintaining acceptable operational characteristics. The work reported herein, although funded by the separate program "Inland Navigation and Flood Damage Reduction," also has the objective of reducing lock costs and focuses on required sill and chamber depths. Significant cost savings can be realized if lock chambers can be raised to reduce construction costs.

At the upstream and downstream ends of a lock, sills are placed which "provide a surface for gate closure and are the structural limits for navigable depth in the lock" (Headquarters, U.S. Army Corps of Engineers 1995). In some cases, the lock miter gates are recessed into the lock floor and the sill elevation is equal to the chamber floor elevation. At other locks, sills are elevated above the chamber floor. At most locks, upper sill depths are greater than lower sill depths because (a) interchangeable miter gates can be used for upper and lower gates if the sill elevations are equal, (b) the upper sill is designed at a low enough elevation to allow passage through the lock in case of loss of upper pool due to accident, or (c) hinged pool operation requires a greater depth at the upper sill. The sill and chamber depth when the lock is in its lowered position, which is equal to the downstream tailwater minus the sill or chamber floor elevation, is the focus of this study. If the sill and chamber depth are too low, the following problems can occur:

a. Tow (barges plus towboat) cannot enter the lock. Old Locks and Dam No. 26 on the UMR experienced low water conditions that prevented tows from entering the lock. This is one factor that led to the

construction of the Chain of Rocks Dam to insure adequate depth over the sill at Locks and Dam No. 26. This suggests the need to establish guidance for minimum sill elevation relative to historical minimum tailwater or anticipated minimum tailwater and not consider only the lower normal pool elevation. Unless economic costs associated with delays are outweighed by the cost to place the lock deep enough to prevent the delays, then consider the lower normal pool elevation.

b. Barges or towboat strike the sill or sill recess and put the lock out of operation.

c. District personnel have reported that after the upbound entering tow builds up the water level in front of the tow, the water rushes out past the tow causing the bow to squat. This can cause the tow to move forward and hit the upper miter gates depending on the tow configuration, ice, sill clearance, and pilot experience. In a similar manner, downbound exiting tows are reported by lock personnel to move upstream and hit the upper miter gates if too much power is applied when shallow chamber depths exist.

d. While the first three problems have occurred, the primary issue regarding sill and chamber depth is the cost of delays associated with excessive time to enter or exit the lock versus the construction cost of deeper locks to reduce the delays. Excessive entry and exit time with shallow sill and chamber depth is caused by the water displaced by the moving tow having a small flow area around the tow, and consequently, a high resistance to flow. When this happens, the entering tow piles up water in front of the tow creating a head differential that limits entry speed. In a similar fashion, the exiting tow results in a reduced water level behind the tow creating a head differential that limits exit speed.

Prevention of tows striking the sill or upper miter gates and the entry/exit time for tows are two of the parameters required in establishing the required elevation of the lock chamber. Another parameter that dictates the required elevation of the lock chamber is the submergence required for the filling and emptying system. The chamber depth required for the F&E system varies with the type system. The F&E system requires a cushion depth or minimum submergence during lock filling operations to avoid excess hawser forces for a tow and barges moored in the chamber. This cushion depth also prevents excessive surface turbulence that could be hazardous to smaller vessels in the lock chamber during filling. Existing guidance developed from lock model studies on submergence requirements for side port systems for 33.5-m- (110-ft-) wide locks can be found in Engineer Manual 1110-2-1604 (Headquarters, U.S. Army Corps of Engineers 1995). The desired minimum submergence for the side port system is 7.0 m (23 ft) for this width lock and is based on a 2.7-m (9-ft-) draft plus one-half of the port spacing, 4.3 m (14 ft). The chamber depth for bottom culvert systems may be controlled by the top elevation of the bottom culverts. At least 4.9 m (16 ft) of depth over the top of the bottom culverts is generally desired for safe filling operations. Davis (1989) indicates the tops of

the bottom culverts should be no higher than the lock sills. Current research results of a bottom culvert system for a 33.5-m- (110-ft-) wide lock reveal that a depth of 4.9 m (16 ft) over the top of the culverts provides acceptable filling conditions (practical valve operation, desired filling time, no excess hawser forces) for lifts up to 11.3 m (37 ft). Additional research results will be available in the near future for submergence requirements for bottom culvert F&E systems. Data presented subsequently show that the submergence specified in the guidance documents is not available at many existing locks.

Objectives and Limitations

The objectives of this study are as follows:

a. Summarize previous studies and existing sill and chamber floor depth guidance.

b. Summarize sill and chamber floor depths at existing locks.

c. Compare entry/exit time for tows as a function of sill and chamber floor depth at existing locks.

d. Recommend guidance for entry/exit times as a function of sill and chamber floor depth.

This study is limited to 366-m- (1,200 ft-) long by 33.5-m- (110-ft-) wide locks because almost all new locks are being constructed to this length.

2 Previous Studies and Existing Guidance

Previous studies and guidance in chronological order are as follows:

a. Rivers and Harbors Act of 1917- "No vessel shall attempt to enter a lock unless it's draft is at least three inches less than the least depth of water over the guard sills, or over the gate sill if there be no guard sill." This statement is at the front of some of the navigation charts produced by the Corps such as USACE (1989).

b. Kooman (1973). "Navigation Locks for Push Tows." Kooman conducted physical model studies in which he looked at the entry/exit times and formation of translation waves in the lock chamber for tows with shallow lock depths both with sills and in flat-floored chambers. He states "From numerous results it is clear that a water depth of 1.6 to 1.7 times the draft can be considered optimal for flat-floored locks used by large push tows. In a lock with sills the water depth over the sill should be roughly 1.5 to 1.6 times the draft." Kooman experimented with flat-floored chambers and 0.5-m- (1.6-ft-) and 1.25-m- (4.1-ft-) high sills above the chamber floor. The width of the tow relative to the lock chamber width for one of Kooman's tows was 22.8 m/24 m = 0.950 for Kooman's experiments which is almost identical to Corps locks of 32 m (105 ft)/33.5 m (110 ft) = 0.955. A 24-m-wide lock was used in all of Kooman's experiments.

For entering tows, the results in Kooman show that the speed of entry is irregular because of the reflection of the wave from the closed upstream gate. Kooman states "A ship entering a comparatively narrow lock causes a translatory wave. This not only considerably retards lock entry, but also makes it irregular, because of continuing backward and forward motions of the wave. The ship's jerky progress with its sudden retardations and accelerations may trap the ship's crew into faulty reactions." Kooman conducted lock entry time studies in a flat floored lock and in a lock with 0.5-m- or 1.25-m-high sills. Figure 1 shows Kooman's results replotted as average entry speed versus blockage factor (BF) for an approach speed, V_o, of 1.5 m/sec and for both the flat-floored lock and the locks with sills. The solid line is based on calculations of the limit speed for the

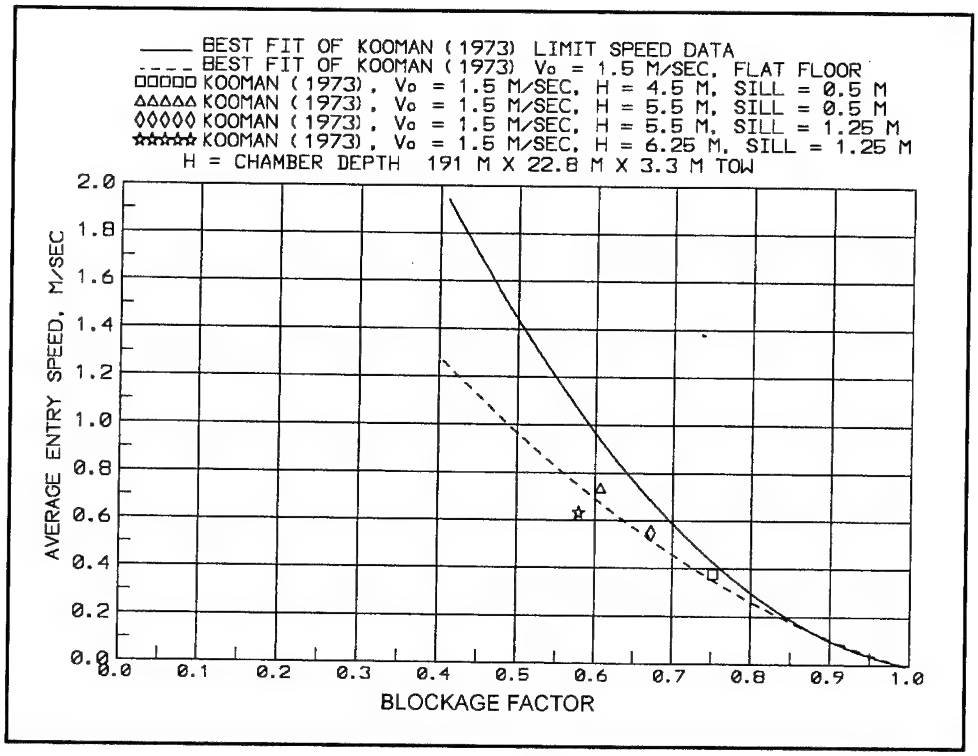

Figure 1. Average entry speed versus BF. Data with and without sills (Kooman 1973)

two different vessels used by Kooman based on Jansen and Schijf (1953) and serves as an upper limit for average entry speed. No self-propelled tow can exceed the limit speed except for a short distance when the waterway cross section abruptly reduces such as at a lock entrance. The dashed line is the best fit of the Kooman data and was forced to go through an average entry speed of 0.0 at a blockage factor of 1.0. Average entry speed in the Figure 1 plot was determined from the distance from the lock entrance (defined as the point where lock walls are 24 m apart) to the bow at the end of the entry divided by Kooman's entry time. At the end of entry, the stern of the towboat was 25 m inside the lock chamber, which means the distance traveled was the tow length plus 25 m. All of Kooman's experiments were conducted with a constant propeller rpm throughout the entry. At the end of entry the tow was still moving, which means that the times posted by Kooman exclude the last step of lock entry which is stopping the tow before it hits the lock gates. Kooman's data will work well for the purposes of this report because we are trying to define the effects of sill and chamber depth on lock entry. Kooman used depth/draft but BF was used because it incorporates the effects of the beam and draft of the tow and the width and depth of the lock. Various means of defining blockage factor as vessel area/channel area were tried in order to get the Kooman data with and without sills to collapse to a single relationship. Various weightings of the lock sill area were tried and the best agreement was found by defining the BF as:

$$BF = \frac{(Beam)\ (Draft)}{[(Lock\ chamber\ area\ +\ 2\ Lock\ sill\ area)/3]} \quad (1)$$

This definition of BF is simply a means of giving a greater weight to the depth over the sill than the depth in the chamber and the comparison of data with and without sills is shown by the dashed line and data points, respectively, in Figure 1 for a velocity of approach V_o of 1.5 m/sec. In Figure 1, H is the chamber depth. Lock sill area is H minus sill height times the lock width. This definition of BF must be limited to the range of the ratio of sill and chamber areas used in Kooman's experiments to prevent giving too much weight to the chamber area for locks having a deep chamber and a shallow sill. Chamber area will be limited to 1.3 (sill area) which is the limit of Kooman's data. While some tows approach the lock entrance at speeds as high as 1.5 m/sec, the majority of tows on the UMR-IWW approach at 1.0 m/sec or less, which is the lowest approach speed used in Kooman's experiments. (Navigation Notice No. 1-1998 for the Mississippi Valley Division and the Great Lakes and Ohio River Division states that tows within 61 m (200 ft) of the lock gates shall proceed at a speed of not greater than 2 mph (0.9 m/sec.) The dashed line in Figure 2 shows the best fit of Kooman's data for average entry speed versus BF for an approach speed of 1.0 m/sec.

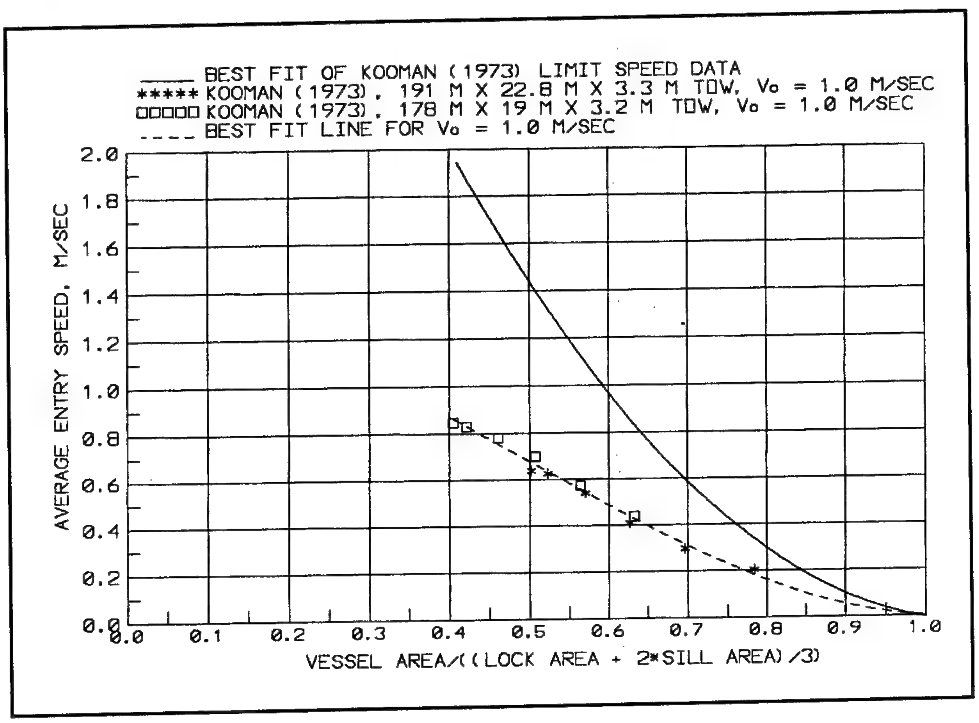

Figure 2. Average entry speed versus BF. Data for 1.0 m/sec approach speed (Kooman 1973)

Kooman conducted lock exit time studies in a flat-floored physical model lock at various depths using two different shallow draft vessels. Lock exit is a much smoother process than entry in terms of vessel speed and lacks significant

variations in speed caused by translatory waves. Results from Kooman shown in Figure 3 are the average exit speed versus the blockage ratio defined in Equation 1. The average exit speed is defined as the distance from the stern of the towboat at the start of propellers to the end of the lock chamber divided by the time from start of propellers to passage of the towboat stern past the end of the lock chamber. The upper solid line is based on the computed limiting speed from Jansen and Schijf (1953) based on the two tows used by Kooman. Kooman ran experiments with 80, 145, 280 rpm's and 350 rpm's propeller speed in the towboat used in the physical model experiments. Both propeller speeds of 280 and 350 rpm's resulted in average exit speed close to the limit speed. Kooman's data support the use of the limit speed curve as an upper limit for average exit speed.

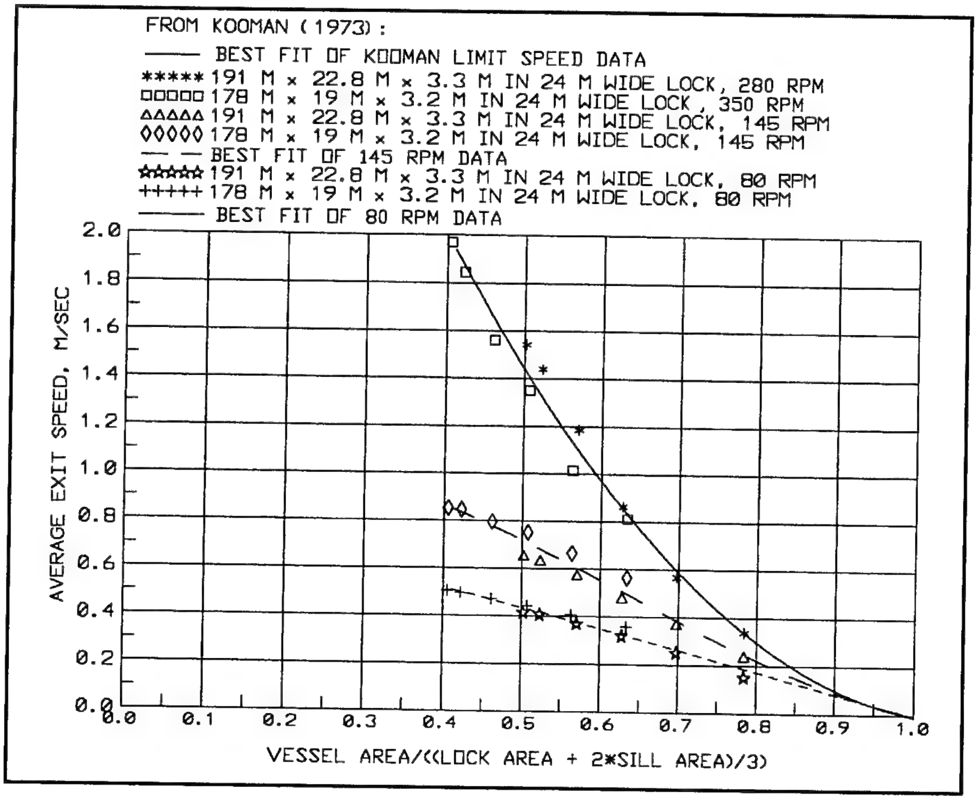

Figure 3. Average exit speed versus BF. Data for 80, 145, 280, and 350 rpm's propeller speed (Kooman 1973)

The dashed lines on Figure 3 are the best fit lines for propeller speeds of 80 and 145 rpm's from both of Kooman's tows. The 145 rpm's propeller speed out of a maximum of 350 rpm's provides a ratio of actual to maximum rpm's that is closest to a typical ratio used on U.S. inland waterways during tow exit. Subsequent U.S. inland waterway data will be used to determine if the 145 rpm's curve is typical of U.S. locks.

c. Engineer Technical Letter 1110-2-223, (HQUSACE 1977) provides the following guidance:

(1) Lower gate sill to be 0 to 0.9 m (0 to 3 ft) above chamber floor when chamber depth ≤ 2 draft + 0.9 m (3 ft).

(2) For chamber depth > 2 draft + 0.9 m (3 ft), the lower sill depth should be at least 2 draft.

(3) Upper sill depth should be at least equal to lower sill depth.

(4) Special operating conditions such as hinged pool operation should be considered for upper sill depth

(5) Additional allowances may be required for ice, debris, or sediment accumulations.

The wording of the ETL, whether intentional or not, places no lower limit on the lower sill depth unless the chamber depth is > 2 draft + 0.9 m (3 ft). For chamber depths < 2 draft + 0.9 m (3 ft), the ETL only says that the sill should be 0 to 0.9 m (3 ft) above the chamber floor. This ETL is frequently interpreted to recommend a minimum sill depth of 2 draft. Earlier in the ETL the comment is made "Experience and research data indicates the gate sill depths should be as great as practical to lessen tow entry and exit times and chamber surges during these maneuvers. A 0.6- or 0.9-m- (2- or 3-ft-) high gate sill or a local recess is often desirable to provide space for gate seating, maintenance work, inspection, and to keep sediment and debris out of the chamber."

d. EM 1110-2-1611 (HQUSACE 1980) provides the following guidance:

(1) Once the chamber floor elevation is established, the sill elevation can be determined.

(2) The gate sill should be as low as possible to allow a large water cross section for displaced water to exit the chamber.

(3) A 0.6- or 0.9-m- (2- or 3-ft-) high gate sill or a local recess is often desirable to provide space for gate seating, maintenance work, inspection, and to keep sediment and debris out of the chamber.

(4) Upper sill depth should be at least equal to lower sill depth.

(5) Comparison studies show increased cost for a higher gate is about equal to the savings in concrete for a low sill.

This guidance brings out the important point that in many cases the chamber depth required for the filling and emptying system dictate how far down in the ground the lock must be placed rather than the

requirements of the sill. This guidance also points out that little can be saved by replacing gate height with concrete.

e. The National Ports Council (NPC) (1980) conducted a study to determine the lockage time for deep draft ships with high BF. The NPC study addressed deep draft ships but many of their results are applicable to shallow draft navigation. NPC develops an analytical method that allows determination of time of entry as a function of vessel power, tug towing power, ship draft and beam, lock sill depth, and factors like the roughness of the lock walls and ship hull. NPC recommended a minimum underkeel clearance of 0.61 m (2 ft). Ship locks frequently have small underkeel clearance compared to shallow draft locks. NPC found good correlation of lock entry times with the blockage factor and found little variation between different ship drafts and widths having the same blockage factor. For blockage factors greater than 0.80, entry times began to increase "fairly rapidly." BF is defined as submerged ship area/ lock area at sill. The entry speed of 3 full-scale ships reported in NPC was 0.3 m/sec or less, which was low compared to shallow draft vessels. NPC found stern squat of ships over the sill to be about 0.30 m (1 ft) and for underkeel clearance of 0.61 m or greater, the likelihood of the stern striking the sill was small. NPC states that a blockage factor of 92 percent "is not yet considered feasible."

f. Maynord (1987). "Safe Speed and Clearance at Lower Sill, Temporary Lock 52, Ohio River"- Tows on the lower Ohio River have struck the sill at the temporary lock at Lock and Dam 52. The Lock 52 lower sill depth at low stages is 3.35 m (11 ft) which provides only 0.6 m (2 ft) below a typical loaded 2.74-m (9-ft) draft tow. As a result of the Lock 52 accidents, a physical model investigation was conducted by Maynord (1987) to look at squat or vertical movement of tows as they pass over the lower sill at Lock 52. Results of the study showed that the maximum squat was at the stern of the towboat. Various combinations of upbound entering tows and downbound exiting tows were evaluated for ranges of propeller rpm and clearance over the sill. The maximum squat was as shown in Table 1.

g. Davis (1989), "Hydraulic Design of Locks"- Guidance in this reference recommends a) Sill depth = 2 draft (available 95 percent of time) and b) Sill depth = 1.7 draft (available 100 percent of time). The Davis guidance (1989) references the Kooman (1973) report as the source of information.

h. EM 1110-2-1604, 1995, "Hydraulic Design of Navigation Locks" provides the following guidance:

(1) A sill depth less than 1.5 draft, except for very low lift .305-m- (0-10-ft-) locks, should not be considered due to safety reasons Kooman (1973).

Table 1
Maximum Squat at Lock and Dam 52 Model Experiments

Experiment No.	Clearance m (ft)	Depth Over Sill, m (ft)	Draft m (ft)	Direction[1]	Maximum Squat, m (ft)	Emptying Valve Position
20	0.46 (1.5)	3.35 (11.0)	2.90 (9.5)	UEN	0.51 (1.66)	Open
44	0.46 (1.5)	3.51 (11.5)	3.05 (10.0)	UEN	0.46 (1.50)	Open
8	0.61 (2.0)	3.35 (11.0)	2.74 (9.0)	DEX	0.41 (1.33)	Open
89	0.61 (2.0)	3.35 (11.0)	2.74 (9.0)	UEN	0.43 (1.42)	Closed
90	0.61 (2.0)	3.35 (11.0)	2.74 (9.0)	UEN	0.50 (1.64)	Closed
28	0.61 (2.0)	3.51 (11.5)	2.90 (9.5)	UEN	0.42 (1.38)	Open
52	0.61 (2.0)	3.66 (12.0)	3.05 (10.0)	UEN	0.46 (1.51)	Open
16	0.76 (2.5)	3.51 (11.5)	2.74 (9.0)	DEX	0.40 (1.32)	Open
36	0.76 (2.5)	3.66 (12.0)	2.90 (9.5)	UEN	0.38 (1.24)	Open
64	0.76 (2.5)	3.81 (12.5)	3.05 (10.0)	DEX	0.35 (1.15)	Open

[1] UEN = upbound entering, DEX = downbound exiting.
Note: maximum squat occurred at the maximum propeller speed tested = 157 rpm's. Opening the downstream emptying valve did not have a major influence on the maximum squat but did increase vessel speed entering or exiting the lock. Results from the study showed a definite correlation of squat with propeller speed. Results from this study showed that the maximum squat for a wide range of conditions was 0.51 m (1.66 ft) for the maximum propeller speed of 157 rpm's used in the experiments.

(2) A normal entry speed of approximately 4.8 km/hr (3 mph) requires a sill depth of 2 draft to avoid excessive squat and loss of vessel speed control.

(3) When gate operating clearance above the floor to allow for some accumulation of trash is necessary, either a 0.6- or 0.9-m- (2- or 3-ft-) height of sill above the floor or a floor recess is provided.

(4) Since there is little difference between the cost of the sill versus the cost of the gate, the sill elevation should be kept as low as possible for ease of tow entry and exit and for safety reasons due to the possibility of grounding caused by squat and/or ice accumulation.

(5) The upper sill depth should be equal to or greater than the lower sill depth.

The "normal" entry speed of 4.8 km/hr 3 mph is large compared to requirements in Navigation Notice No. 1-1998.

i. Borland (1987), "Progress Report on the Barge Profiling System at Lock 26, Mississippi River." The U.S. Army Engineer Cold Regions Research Engineering Laboratory installed transducers at the upper sill of old Lock and Dam 26 to measure the thickness of accumulated ice on the

hull of the barges. Unfortunately, ice accumulation was not severe during the period the transducers were in place.

The guidance in these various documents will be compared to sill depths in use at Corps projects in a subsequent section.

3 Sill and Chamber Depths at Existing Corps Shallow Draft Navigation Projects

General Observations

Sill depths and other lock characteristics at existing Corps projects having 33.5-m- (110-ft-) wide locks are shown in Table 2. The draft used to compute the ratio of lower sill depth/draft was 2.74 m (9 ft) and the lower sill depth was based on the lower normal pool elevation. From Table 2, it is obvious that many locks have sill depths lower than the current guidance of up to twice the draft. As far as the guidance given by Davis (1989), only 21 out of the 106 have sill depth/draft greater than 1.7 which Davis says is required 100 percent of the time. Compared to the least conservative guidance in EM 1110-2-1611 (HQUSACE 1980) that suggests sill depth/draft of 1.5 or greater unless the lock is very low lift (0-3.05 m), 18 of the 106 locks have sill depth/draft < 1.5 and lift greater than 3.05 m. Twelve of the 106 locks have sill depth/draft < 1.5 and are very low lift locks.

Site visits were made to 20 existing Corps locks shown in Table 2 to determine problems associated with shallow sill depths. The site visits focused on the projects having the lowest sill depth/draft ratios and were conducted in the fall of 1998 to observe minimal water depths while still having the chance for some tow traffic. Questions and issues addressed during these visits were as follows:

a. Is there any record of tows striking the sill? What precautions or draft limitations are imposed during low water conditions? What are typical draft of barges and towboats using the lock during low and normal stages on the river?

b. Obtain stage frequency curve for as many locks as possible.

c. Are there problems with entry/exit speed at the lock, particularly at low water conditions?

Table 2
Sill Depths and Lock Characteristics at Corps Projects with 33.5-m-Wide Locks

LOCKNA	ABBREV	RIVER	LOCKSIZ	UPEL[1]	LPEL	UPSE	LOSE	UPSD	LOSD	LIFT	LOSD/DR[2]
NORRELL	NOR	ARKANSA	600	142	112	126	97	16	15	30	1.67
LD2	LD2	ARKANSA	600	162	142	144	128	18	14	20	1.56
JHARDIN	LD3	ARKANSA	600	182	162	164	148	18	14	20	1.56
ESANDER	LD4	ARKANSA	600	196	182	178	168	18	14	14	1.56
LD5	LD5	ARKANSA	600	213	196	195	182	18	14	17	1.56
DDTERRY	TER	ARKANSA	600	231	213	213	199	18	14	18	1.56
MURRAY	MUR	ARKANSA	600	249	231	231	217	18	14	18	1.56
TOADSF	TOA	ARKANSA	600	265	249	247	235	18	14	16	1.56
AVORMO	LD9	ARKANSA	600	284	265	266	251	18	14	19	1.56
DARNL	DAR	ARKANSA	600	338	284	321	270	17	14	54	1.56
OZARKJT	OZA	ARKANSA	600	372	338	354	321	18	17	34	1.89
JWTRIMB	DL13	ARKANSA	600	391	372	374	356	17	16	19	1.78
WDMAYO	MAY	ARKANSA	600	412	391	397	377	15	14	21	1.56
RSKERR	KER	ARKANSA	600	460	412	442	398	18	14	48	1.56
WEBFAL	WEB	ARKANSA	600	490	490	471	444	19	16	30	1.78
AISELDO	SEL	BL WAR	600	95	73	82	60	13	13	22	1.44
WBOLIVE	OLI	BL WAR	600	123	95	110	77	13	18	28	2.00
HOLT	HOL	BL WAR	600	186	123	171.5	109.9	14.5	13.1	63	1.46
BANKHEA	BAN	BL WAR	600	255	186	239	173	16	13	69	1.44
LAGRANG	LAG	ILLINOIS	600	429	419	413.5	406	15.5	13	10	1.44
PEORIA	PEO	ILLINOIS	600	440	429	424.5	417	15.5	12	11	1.33
STARROK	STA	ILLINOIS	600	459	440	442	426	17	14	19	1.56
MARSEIL	MAR	ILLINOIS	600	483.3	459	464.7	445	18.6	14	24.3	1.56
DRESDEN	DRE	ILLINOIS	600	505	483.3	488.2	471	16.8	12.3	21.7	1.37
BRANDO	BRA	ILLINOIS	600	539	505	521.2	491.2	17.8	13.8	34	1.53
LOCKPO	LOC	ILLINOIS	600	578.6	539	558	524	20.6	15	39.6	1.67
HHEFLIN	HEF	TNTM	600	109	73	94	58	15	15	36	1.67
TOMBEVI	BEV	TNTM	600	136	109	121	94	15	15	27	1.67
JSTENNIS	STE	TNTM	600	163	136	148	121	15	15	27	1.67
ABERDEE	ABE	TNTM	600	190	163	175	148	15	15	27	1.67
AMORY	AMO	TNTM	600	220	190	205	175	15	15	30	1.67
GWILKINS	WLK	TNTM	600	245	220	227	202	18	18	25	2.00
FULTON	FUL	TNTM	600	270	245	252	227	18	18	25	2.00
JRANKIN	RAN	TNTM	600	300	270	282	252	18	18	30	2.00
SMONTG	MGM	TNTM	600	330	300	312	282	18	18	30	2.00

(Sheet 1 of 3)

Note: UPEL = Upper Pool Elevation; LPEL = Lower Pool Elevation; UPSE = Upper Sill Elevation; LOSE = Lower Sill Elevation; UPSD = Upper Sill Depth, ft; LIFT = Difference in upper and lower pool elevation; DR = Draft = 9 ft

[1] All elevations are in feet referenced to the National Geodetic Vertical Datum.

[2] Draft is in feet (To convert feet to meters, multiply number of feet by 0.3048).

Table 2 (Continued)

LOCKNA	ABBREV	RIVER	LOCKSIZ	UPEL	LPEL	UPSE	LOSE	UPSD	LOSD	LIFT	LOSD/DR
WHITTEN	WHI	TNTM	600	408	330	393	315	15	15	78	1.67
KENTUCK	KEN	TENN	600	359	303	335	289	24	14	56	1.56
PICKMAIN	PKM	TENN	1000	414	359	395	342	19	17	55	1.89
PICKAUX	PKA	TENN	600	414	359	398	342.2	16	16.8	55	1.87
WILSON	WIL	TENN	600	508	414	493.3	397	14.7	17	94	1.89
WHEELE	WHE	TENN	600	556	508	535	491.3	21	16.7	48	1.86
GUNTERS	GUN	TENN	600	595	556	578	537.3	17	18.7	39	2.08
NICKAJA	NCK	TENN	600	634	595	618.5	580	15.5	15	39	1.67
COFFEEV	COF	TOM	600	33	-1	11	-14	22	13	34	1.44
DEMOPO	DEM	TOM	600	73	33	56	20	17	13	40	1.44
LOCK 27	L27	MISS	1200			380	360	19		0	0.00
MELVIN P	MPM	MISS	1200	419		400	377	19		419	0.00
MELVIN P	MPA	MISS	600	419		400	377	19		419	0.00
LOCK 25	L25	MISS	600	434	419	415	407	19	12	15	1.33
LOCK 24	L24	MISS	600	449	434	430	422	19	12	15	1.33
LOCK 22	L22	MISS	600	459.5	449	441.5	435.5	18	13.5	10.5	1.50
LOCK 21	L21	MISS	600	470	459.5	453.5	447.5	16.5	12	10.5	1.33
LOCK 20	L20	MISS	600	480	470	165	458	15	12	10	1.33
LOCK 19	L19	MISS	1200	518	480	503	467	15	13	38	1.44
LOCK 18	L18	MISS	600	528	518	511.5	504.5	16.5	13.5	10	1.50
LOCK 17	L17	MISS	600	536	528	520	515	16	13	8	1.44
LOCK 16	L16	MISS	600	545	536	528	524	17	12	9	1.33
LOCK 15	L15	MISS	600	561	545	534	534	27	11	16	1.22
LOCK 14	L14	MISS	600	572	561	551.5	547.5	20.5	13.5	11	1.50
LOCK 13	L13	MISS	600	583	572	564	559	19	13	11	1.44
LOCK 12	L12	MISS	600	592	583	575	570	17	13	9	1.44
LOCK 11	L11	MISS	600	603	592	584.5	579.5	18.5	12.5	11	1.39
LOCK 10	L10	MISS	600	611	603	596	591	15	12	8	1.33
LOCK 9	LD9	MISS	600	620	611	604	598	16	13	9	1.44
LOCK 8	LD8	MISS	600	631	620	609	606	22	14	11	1.56
LOCK 7	LD7	MISS	600	639	631	621	619	18	12	8	1.33
LOCK 6	LD6	MISS	600	645.5	639	628.5	626.5	17	12.5	6.5	1.39
LOCK 5A	L5A	MISS	600	651	645.5	633	633	18	12.5	5.5	1.39
LOCK 5	LD5	MISS	600	660	651	642	639	18	12	9	1.33
LOCK 4	LD4	MISS	600	667	660	650	647	17	13	7	1.44
LOCK 3	LD3	MISS	600	675	667	658	653	17	14	8	1.56
LOCK 2	LD2	MISS	600	687	675	665	662	22	13	12	1.44
EMSWOR	EMS	OHIO	600	710	692	693	679.1	17	12.9	18	1.43
DASHIELD	DAS	OHIO	600	692	682	678.6	663.5	13.4	18.5	10	2.06
MONTGO	MON	OHIO	600	682	664.5	666	649.9	16	14.6	17.5	1.62

(Sheet 2 of 3)

Table 2 (Concluded)											
LOCKNA	ABBREV	RIVER	LOCKSIZ	UPEL	LPEL	UPSE	LOSE	UPSD	LOSD	LIFT	LOSD/DR
CUMBERL	CMM	OHIO	1200	664.5	644	652	629.2	12.5	14.8	20.5	1.64
CUMBERL	CMA	OHIO	600	664.5	644	652	629.2	12.5	14.8	20.5	1.64
PIKE ISLA	PIM	OHIO	1200	644	623	627	608.2	17	14.8	21	1.64
PIKE ISLA	PIA	OHIO	600	644	623	627	608.2	17	14.8	21	1.64
HANNIBAL	HNM	OHIO	1200	623	602	587.2	587.2	35.8	14.8	21	1.64
HANNIBAL	HNA	OHIO	600	623	602	606	587.2	17	14.8	21	1.64
WILLOW I	WIM	OHIO	1200	602	582	574.6	567	27.4	15	20	1.67
WILLOW I	WIA	OHIO	600	602	582	574.6	567	27.4	15	20	1.67
BELLEVILL	BLM	OHIO	1200	582	560	562	545	20	15	22	1.67
BELLEVILL	BLA	OHIO	600	582	560	562	545	20	15	22	1.67
RACINE	RAM	OHIO	1200	260	538	542	523	18	15	22	1.67
RACINE	RAA	OHIO	600	260	538	542	523	18	15	22	1.67
RCBYRD	RBM	OHIO	1200	538	515	520	497	18	18	23	2.00
RCBYRD	RBA	OHIO	600	538	515	510	497	28	18	23	2.00
GREENUP	GRM	OHIO	1200	515	485	497	470	18	15	30	1.67
GREENUP	GRA	OHIO	600	515	485	497	470	18	15	30	1.67
MELDAHL	MEM	OHIO	1200	485	455	467	440	18	15	30	1.67
MELDAHL	MEA	OHIO	600	485	455	467	440	18	15	30	1.67
MARKLAN	MRM	OHIO	1200	455	420	430	405	25	15	30	1.67
MARKLAN	MRA	OHIO	600	455	420	430	405	25	15	35	1.67
MCALPIN	MCM	OHIO	1200	420	383	402	371	18	12	37	1.33
MCALPIN	MCA	OHIO	600	420	383	402	367	18	16	37	1.78
CANNELT	CNM	OHIO	1200	383	358	368	343	15	15	25	1.67
CANNELT	CNA	OHIO	600	383	358	368	343	15	15	25	1.67
NEWBUR	NEM	OHIO	1200	358	342	340	326	18	16	16	1.78
NEWBUR	NEA	OHIO	600	358	342	340	326	18	16	16	1.78
JTMYERS	JMM	OHIO	1200	342	324	322	308	20	16	18	1.78
JTMYERS	JMA	OHIO	600	342	324	322	308	20	16	18	1.78
SMITHLAN	SMM	OHIO	1200	324	302	290	267	34	15	22	1.67
SMITHLAN	SMA	OHIO	600	324	302	290	267	34	15	22	1.67
LOCK 52	52M	OHIO	1200	302	290	286.6	279	15.4	11	12	1.22

(Sheet 3 of 3)

d. Is the downstream emptying valve open during downstream entry/exit?

e. While at the lock, measurements of entry and exit speed and time will be made for loaded 3 wide by 5 long tows.

f. What are the concerns relative to ice accumulation on the barges at the lock? When do icing problems occur?

g. What are typical propeller speeds for towboats' entry/exit and is there any circumstance where the towboat runs at high rpm's while over the sill?

Results from Upper Mississippi River Site Visits

Site visits to 11 Upper Mississippi River locks and five Illinois Waterway locks were conducted during 21-30 September 98. A summary of the observations follows:

a. With the exceptions of the 366-m- (1,200-ft-) × 33.5-m- (110-ft-) locks at Locks 27, Melvin Price, and Lock and Dam 19, all locks on the UMR-IWW are 183-m- (600-ft-) by 33.5-m- (110-ft-). Since the majority of tows are longer than 183 m, double lockages are the typical lockage on the UMR-IWW. Tow speeds/times in and out of the 183-m locks using double lockages on most UMR-IWW locks are not applicable to single lockages at 366-m-long locks that are generally considered for new lock construction.

b. Lower sill depths on the UMR averages 3.9 m (12.8 ft) and range from 3.35 m - 4.57 m (11-15 ft). Lower sill depths on the IWW averages 4.1 m (13.4 ft) and range from 3.66 m - 4.57 m (12-15 ft). Based on stage- frequency data provided by the Rock Island District, 95 percent of the time the lower sill depth is about 0.18 m (0.6 ft) greater than the depth provided by the normal lower pool elevation. The stage-frequency curve for Lock and Dam 19 is shown in Figure 4 and is typical of other locks on the UMR. The stage-frequency provides the data needed to determine the duration of water levels causing significant delays. For example, Figure 4 shows that the lower pool at Lock 19 is at or below el 481.0 (0.3 m (1 ft) above lower normal pool) for 22 percent of the time. In the absence of ice, none of the locks reported incidents of a tow striking the sill (including L&D 15 where the lower sill depth is 3.35 m (11 ft)) or believed they had a problem at their lock with excessive entry/exit times that were related to sill depth. Most locks leave their emptying valves open to facilitate upbound entry and downbound exit, particularly during low stages.

c. During winter months, the severity of ice problems varies significantly along the length of the UMR. The locks in the St. Paul District have the most severe winters, but because the river freezes up rapidly and navigation effectively ceases, ice problems with navigation are not severe. Downstream of the St. Paul District, climatic conditions lead to less cold winters where navigation continues, but frazzled and brash ice forms and can readily adhere to the bottom of the barges. Significant problems with this type of ice were estimated to occur every 3-5 years. Most navigation during winter months is limited to Lock 19 and below. At Old Lock 26, the thickness of accumulated ice has been estimated by

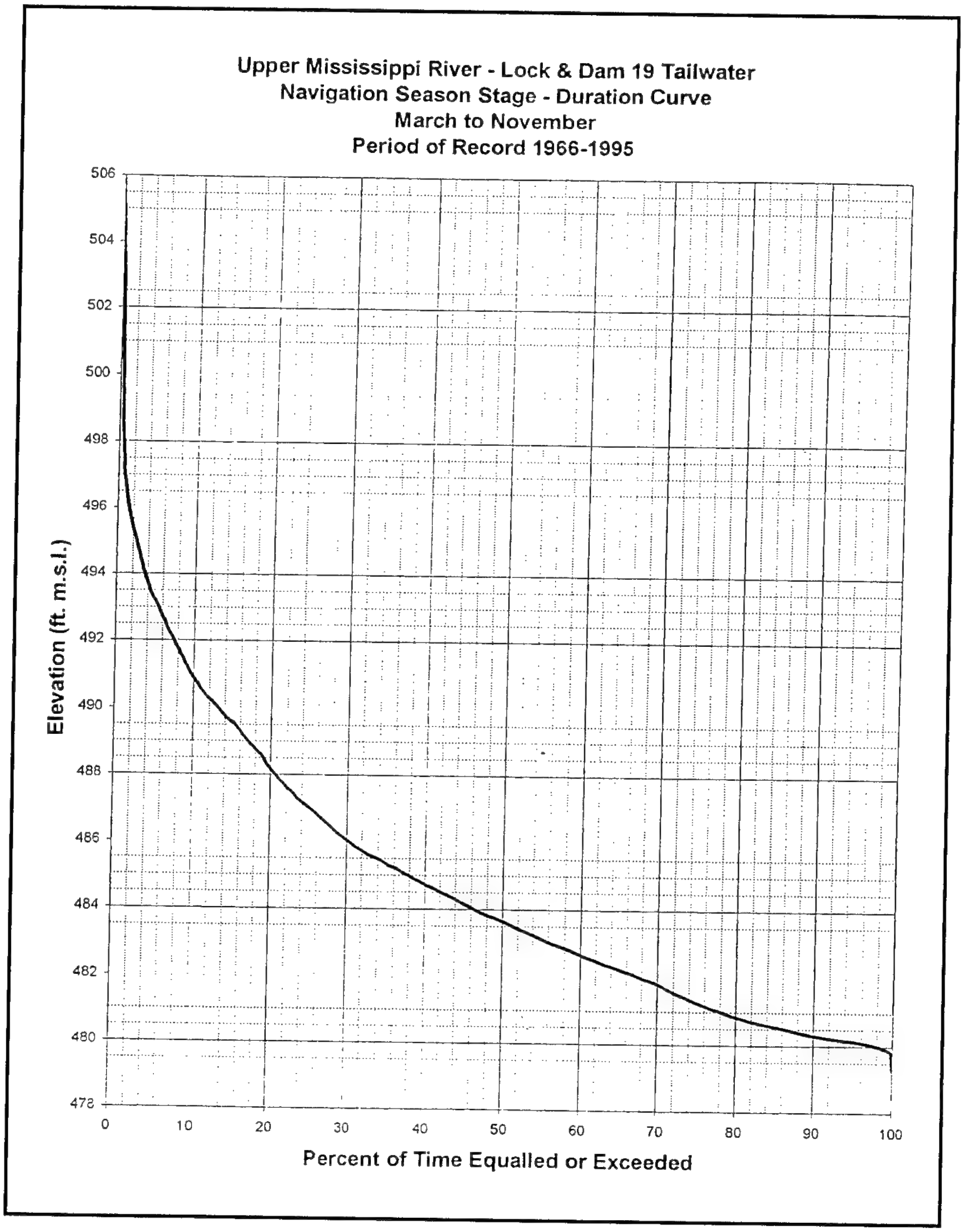

Figure 4. Upper Mississippi River - Lock and Dam 19 tailwater navigation season stage - duration curve March to November, period of record 1966-1995

lock personnel to be as much as 2.4-3.0 m (8-10 ft) below the bottom of the barges under extreme conditions. Channel depth would limit ice accumulation to less than 2.4-3.0 m on most reaches of the UMR and IWW. Because upper sill depths are larger, downbound tows pass over the upper sill with ice attached with fewer problems than at the lower sill. When the chamber is lowered, a few tows have sat down on top of the ice and broken wires in the tow. At old Lock and Dam 26 on the UMR, tows loosened their wires prior to lowering of the chamber during severe ice

periods. To exit the lock downbound during severe ice, the tow is either flushed out of the lock by partially opening the filling valves and/or the tow shoves into the lower sill to scrape the ice off the bottom of the barges and move out of the lock. While this creates a delay to tow movement, damage to sills has not been observed. On the IWW, ice problems have been less severe because of chemical and thermal effects on the river. However, in recent years, reduction of chemical pollution on the IWW has resulted in ice accumulations where they previously did not occur. None of the IWW locks reported problems with ice shearing off the bottom of the barge, but one lockmaster suggested the shallowness of the IWW prevents significant accumulation on the bottom of the barges. Both UMR and IWW reported ice problems that required ice lockages to remove ice in the upper approach before attempting to lock tows. This problem was not felt to be strongly affected by sill depth. Almost all UMR-IWW locks limit traffic to two barge wide tows during severe ice conditions. One lock person said that during severe ice, mooring lines were not needed during locking because the ice kept the tow from moving. Ice on the bottom of barges at the 3.7-4.1 m (12 - 13.5 ft) lower sill depths on the UMR locks 19-25 cause significant delays during downbound exit. The lockmaster at Old Lock and Dam 26 reported significant delays at the upper sill with a 4.3-m (14-ft) upper sill depth as did the lockmasters at Lock and Dam 19 and 20 which have 4.57-m (15-ft) upper sill depth. Lock 21 (upper sill depth = 5.0 m (16.5 ft)) reported few ice problems. Locks 24 and 25 have 5.8-m (19-ft) upper sill depths and did not report significant delays at the upper sill. Minimum sill depths (upper or lower) of somewhere between 4.57 m (15 ft) and 5.8 m (19 ft) are recommended to prevent ice related delays. The cost of extra lock depth to prevent ice related delays would have to be weighed against the cost and frequency of occurrence of such delays.

Results from Ohio River Site Visits

Site visits to four Ohio River locks (McAlpine, Markland, Meldahl, and Greenup) were conducted during 9-13 November 1998. A summary of the observations follows:

a. With the exception of Emsworth, Dashield, and Montgomery, all main locks on the Ohio River are 366 m (1,200 ft) in length. With the exception of McAlpine Lock, the four locks visited have 4.57 m (15 ft) lower sill depths when measured at lower normal pool elevation.

b. McAlpine is a rather unique lock on the Ohio River because it has only a 3.66 m (12 ft) lower sill depth at normal lower pool elevation. The next downstream pool, Cannelton, was never raised to its expected level and was left 0.9 m (3 ft) lower than originally designed. Only the temporary lock at Locks and Dam 52 has a lesser lower sill depth (as low as 3.35 m (11.0 ft)) than McAlpine on the Ohio River. Lock personnel at McAlpine

reported no problems with tows striking the lower sill but did report problems with excessive entry time at stages close to the normal lower pool elevation. Lock personnel also report that tows on the Ohio River frequently exceed 2.74 m (9 ft) draft which makes the entry/exit problems even more severe. Tows exceeding 2.74 m (9 ft) are not uncommon on the UMR as well. Personnel report that at least one tow pilot stated that the shallow depth over the lower sill at McAlpine resulted in excessive propeller vibration during passage over the lower sill. Problems also occur in the lower approach channel due to shallow depths. Although ice accumulation of 0.9-1.5 m (3-5 ft) below the barges has been seen on the Ohio, ice is not considered a big problem at McAlpine.

c. Markland, Meldahl, and Greenup reported no problems with tows striking the sill nor did they observe problems with excessive entry/exit time. At Meldahl the Lockmaster said that the desired entry/exit speed in the Huntington District is 0.5 m/sec (100 ft/min or 1.1 mph). This speed is mainly a desired speed for safety of entering tows, particularly loaded, entering tows. Exiting tows often leave faster because they do not have to stop and they may be facing adverse wind or outdraft conditions that require significant vessel speed. Emptying valves are left open during downbound exit or upbound entry during low stages at all but McAlpine Lock.

4 Observed Entering and Exiting Times versus Blockage Factor Using LPMS Data

Exit Speed

Exit results are expressed in speed to compare to the Kooman curve, but subsequent comparisons will focus on time for both entry and exit. Figure 5 shows average exit speed data observed by the author during the Ohio River site visits reported herein and reported in Maynord (1987) at Lock and Dam 52. Exit speed of the field data is defined as the average speed of the tow while the barges are over the lower sill. This was determined by timing the passage of the bow, junctions between barges, and the stern of the barges as they passed the lower sill and using the length of the barges to determine the speed. The author's data (rpm's unknown) scatter about Kooman's exit speed curves for constant propeller speeds of 80 and 145 rpm's with most of the non-Lock 52 data closer to the 145 rpm's curve. Note that Kooman makes no mention of emptying valves being opened (or even present) so it is assumed that the valves are closed. Lines A, B, and C show the BF for locks having 0.3-m- (1-ft-) high sills above the floor for sill depths of 5.49 m (18 ft), 4.57 m (15 ft), and 3.65 m (12 ft) for a typical 32 m wide (105 ft) by 2.74 m (9 ft) draft tow in a 33.5-m- (110-ft-) wide lock.

Entry Time

Lock Performance Monitoring System (LPMS) data were obtained from the Districts for Lock and Dam 19, Melvin Price, and Lock 27 on the UMR and McAlpine, Markland, and Cannelton on the Ohio River. Chamber floor or top of lateral elevations are: Lock 19 = 466.5, Melvin Price = 374.0, Lock 27 = 348.0, Markland = 404.0, McAlpine = 370.0, and Cannelton = 343.0. Data were limited to upbound, entering tows because the times "bow over sill" (BOS) and "end of entry" (EOE) were the only two times in the LPMS data whose

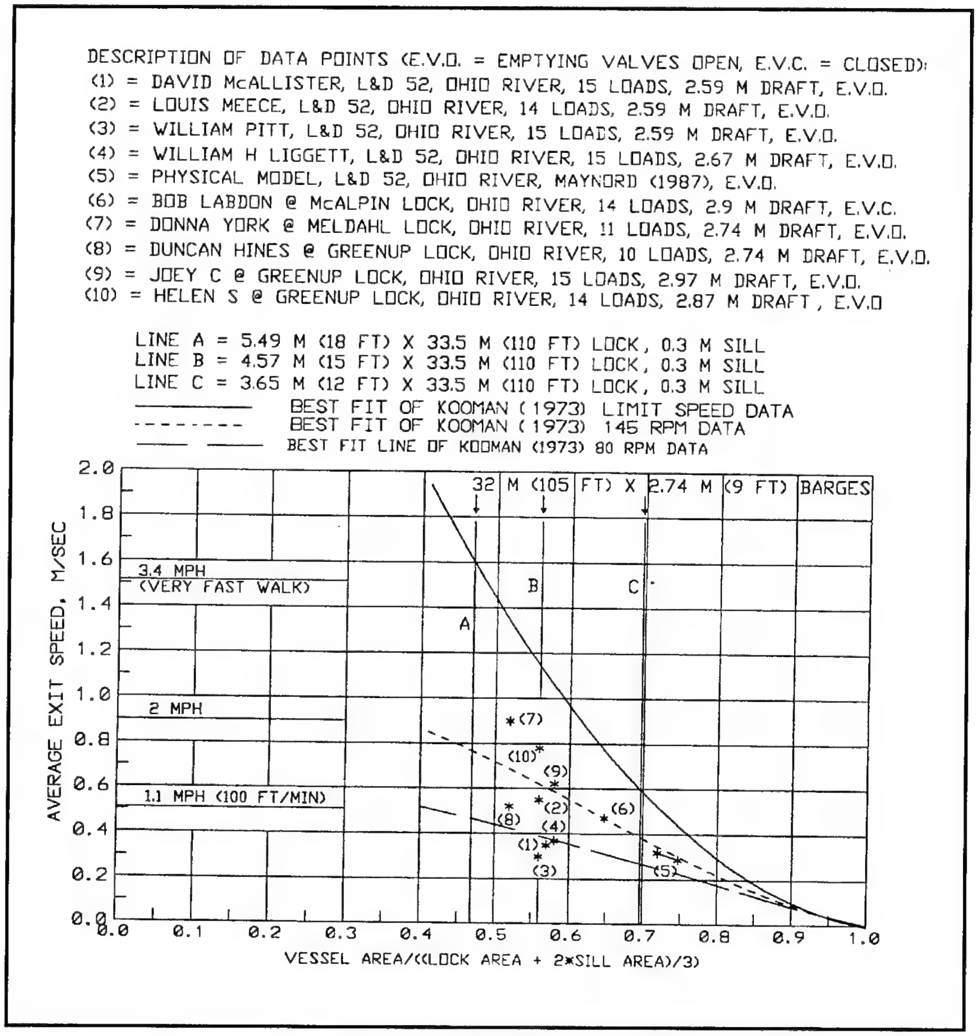

Figure 5. Average exit speed versus BF comparison with Ohio River data (To convert feet to meters, multiply number of feet by 0.3048)

difference, defined as entry time T_e, could be closely correlated to sill and chamber depth effects. BOS is self explanatory. EOE is the earliest of the following times: (1) When the tow has entered the lock and has been secured within the lock and the gates are clear or (2) when the lockman starts closing the gates. In addition to variation from the effects of sill and chamber depth, the LPMS data for entry time have a large amount of scatter resulting from various environmental, human, and navigation factors. These factors include:

a. Environmental:

(1) Day/night.

(2) Precipitation/fog.

(3) Lighting at lock.

(4) Ice, wind.

b. Human:

(1) Different pilots and crews (experience, mood, concern, etc).

(2) Company policy.

(3) Lockman (accuracy of times entered and reluctance to enter large times which requires documenting some type of delay).

c. Navigation Factors:

(1) Tow draft, beam, length.

(2) Presence of traffic, type of entry (fly, exchange, turnback).

(3) Maneuverability, power of tow.

(4) Type of cargo.

(5) Dredging or other activities in lock approach.

It would be difficult to develop or use a model that accounted for all of these factors. Attempts were made to segregate data from the LPMS to determine correlations to some of them. Comparisons were made with day and night tows using 1997 data at Markland and McAlpine locks and no difference was observed between entry time of day and nighttime tows. Comparisons were made of entry types fly, turnback, and exchange using Lock and Dam 19 data and no differences in entry time were observed. The following section describes how the data were used to define the effects of sill and chamber depth.

Entry Time for Various Tow and Chamber Configurations

In the evaluation of entry time, three different tow and chamber conditions, specifically, unloaded tows, loaded tows in deep depths, and loaded tows in shallow depths were considered in the following paragraphs:

a. *Unloaded tows.* Operation of unloaded tows differs from loaded tows because of their greater ability to stop and possibly lesser consequence of striking miter gates. BF is not an important parameter for unloaded tows because observed entry speeds are far less than the speed at which the chamber or sill depth exerts any significant influence on the unloaded tow. Observed data are plotted in Figure 6 to see if entry time for unloaded tows is a function of the sill depth/towboat draft which would reflect the pilot's concern for the towboat striking the sill at shallow depths. Because the LPMS data do not show towboat draft, a draft of 2.74 m (9 ft) was used in Figure 6 for all towboats. The 1,497 data points

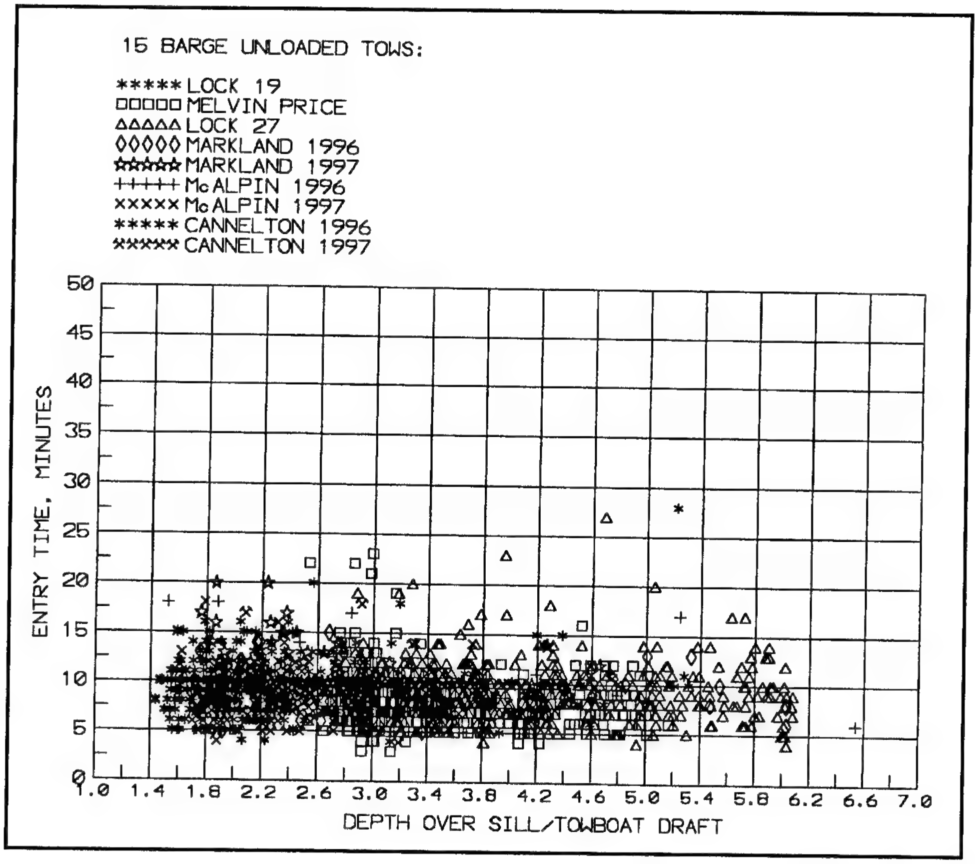

Figure 6. Entry time versus sill depth/towboat draft 15 barge unloaded tows

from three UMR and three Ohio River locks show little variation of entry time with sill depth/towboat draft. If a relationship exists between T_e and depth/draft, it would be expected at the lowest depth/draft. The best fit line for the 219 unloaded tows having depth/towboat draft ≤ 2.0 (T_e = 10.7-0.72 depth/draft) varied from 9.7 min at depth/draft = 1.45 (minimum of data) to 9.3 min at depth/draft = 2.0. The average entry time for all 1,497 unloaded tows is 9.1 min with a standard deviation of 2.9 min and a range as shown in Figure 6. Due to the small difference between all data and data for depth/draft < 2, an entry time of 9.1 min is the average for all unloaded, upbound, entering tows.

b. Loaded tows, BF < 0.35. Similar to unloaded tows, observed entry speeds of loaded tows at small BF (deep chamber and sill depths) are far less than the speed at which the chamber or sill depth exerts any significant influence on the entry time of the loaded tow. All of the loaded tow data were evaluated to determine when the data are affected by the value of BF. Average entry time for all data from the 6 locks was determined for ranges of BF of lower limit of data up to BF = 0.25, then lower limit of data up to BF = 0.30, and so on up to lower limit of data up to BF = 0.50. For all entry time data having BF less than 0.35, the entry time for 2,007 loaded tows from three UMR and three Ohio River locks

was not dependent on BF and averaged 13.0 min as shown in Figure 7. The standard deviation was 3.9 min.

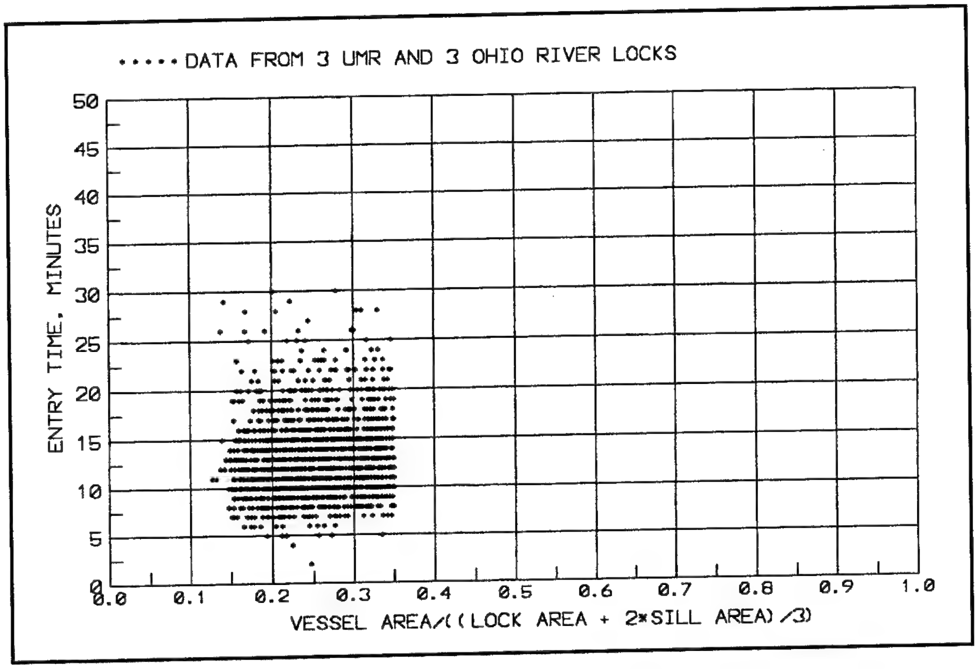

Figure 7. Entry time versus BF (BF < 0.35)

c. *Loaded tows, large BF.* For BF ≥ 0.35, entry time varies with BF along with many of the environmental, human and navigation factors given. Figures 8-14 show entry time versus BF for Lock 19 on the UMR and Markland, McAlpine, and Cannelton Locks on the Ohio River. Melvin Price and Lock 27 were not used because they have very little data above BF = 0.35. Best fit equations of the form

$$T_e = A \exp [B (BF)] \tag{2}$$

are given in Table 3 and show similar times at the four locks.

Table 3
Best Fit Equations for Upbound Loaded Tows Having BF > 0.35

Lock	Coefficients A and B in Equation 2.
Lock and Dam 19	7.55, 1.45
Markland 1996	9.77, 1.00
Markland 1997	10.47,0.82
McAlpine 1996	9.73, 1.30
McAlpine 1997	8.80, 1.48
Cannelton 1996	12.42, 0.53
Cannelton 1997	5.83, 2.29

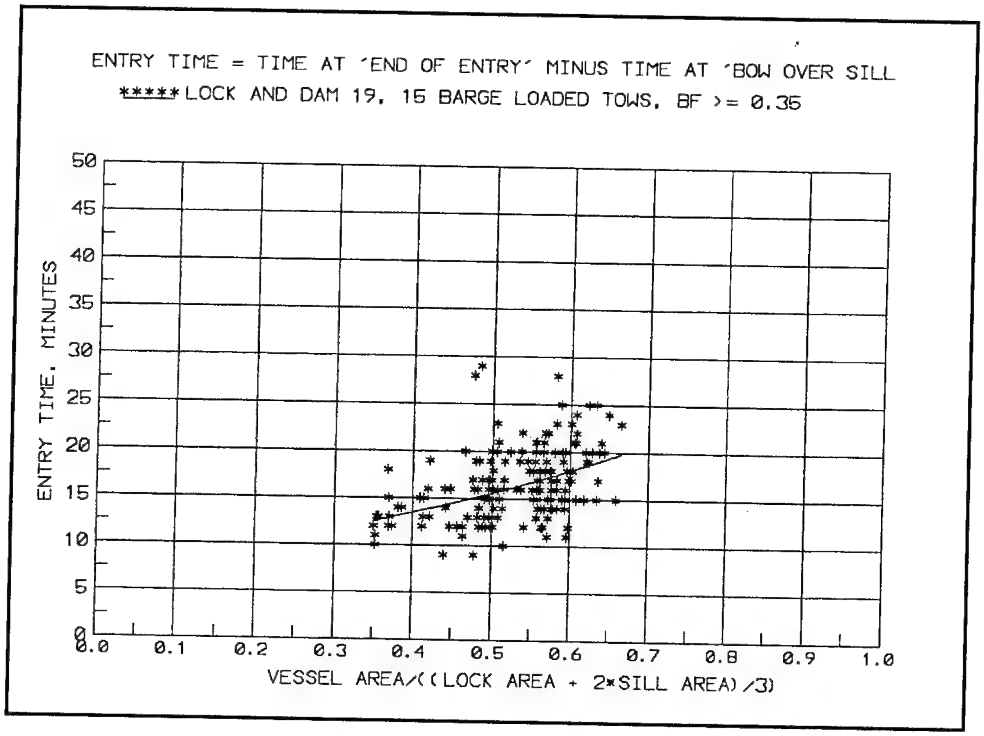

Figure 8. Entry time versus BF Lock and Dam 19 (BF > 0.35)

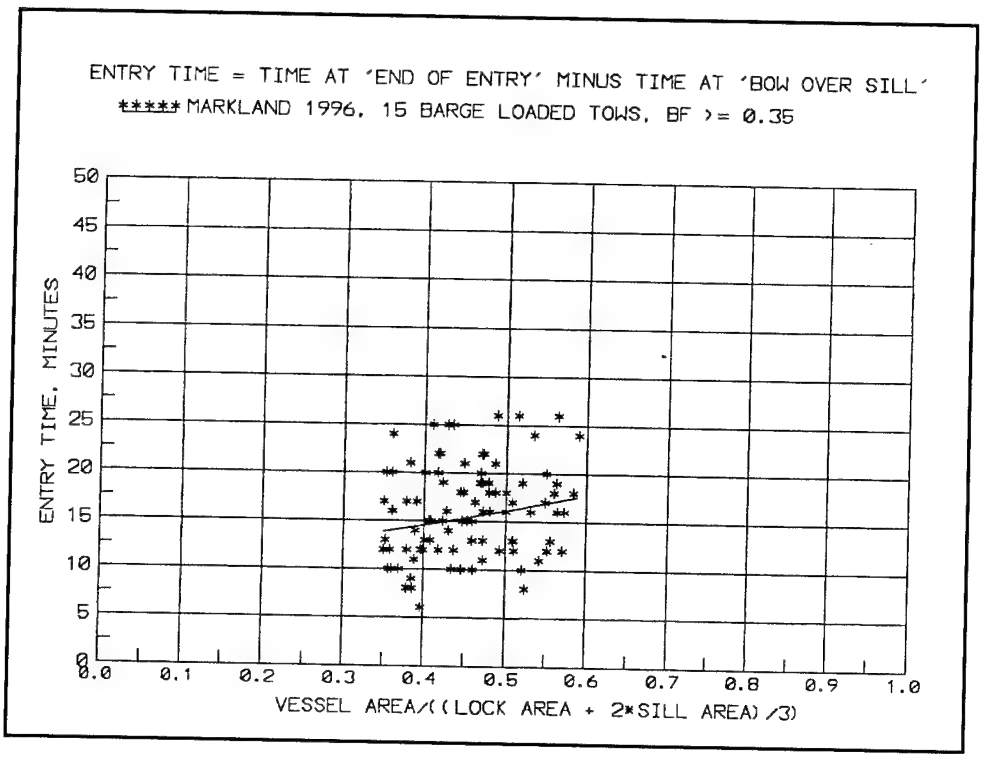

Figure 9. Entry time versus BF Markland Lock, 1996 (BF > 0.35)

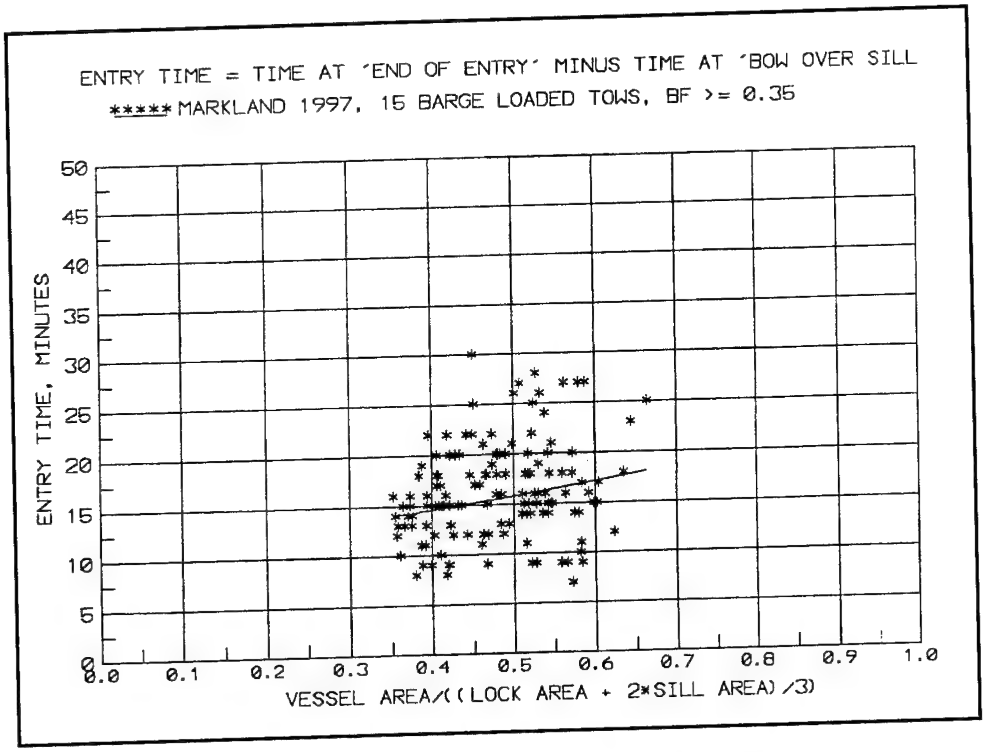

Figure 10. Entry time versus BF Markland Lock, 1997 (BF > 0.35)

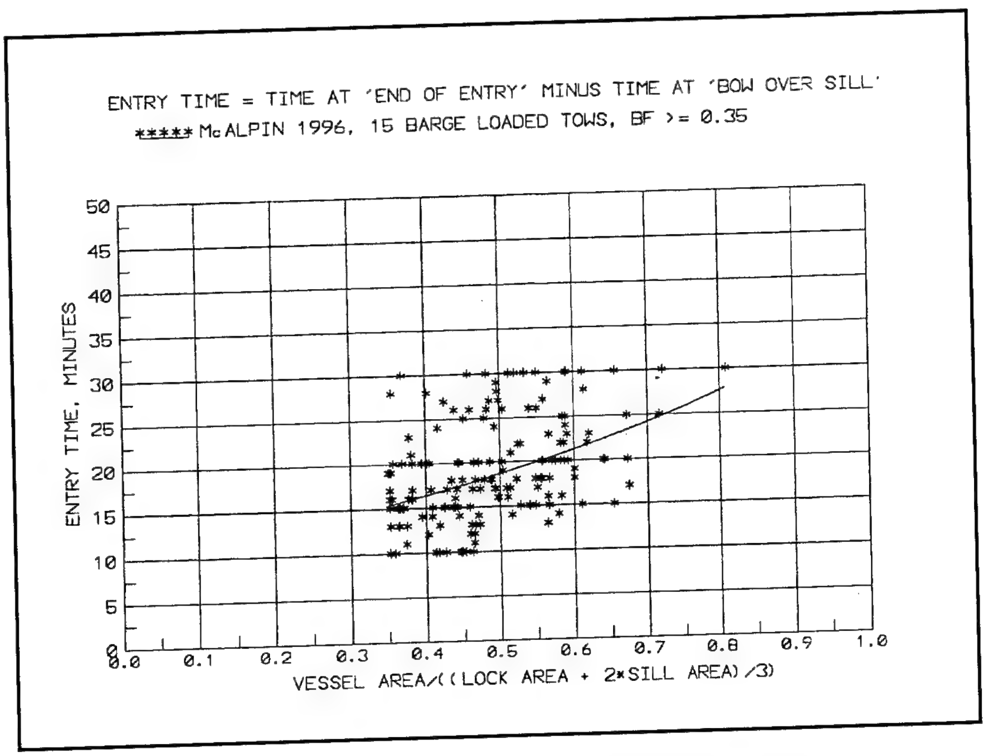

Figure 11. Entry time versus BF McAlpin Lock, 1996 (BF > 0.35)

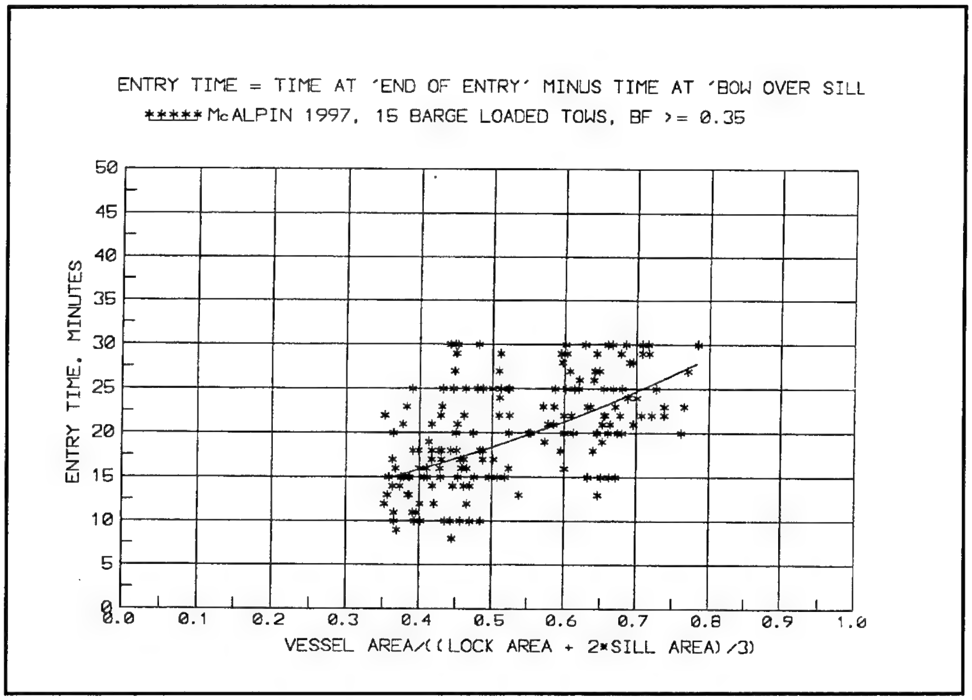

Figure 12. Entry time versus BF McAlpin Lock, 1997 (BF > 0.35)

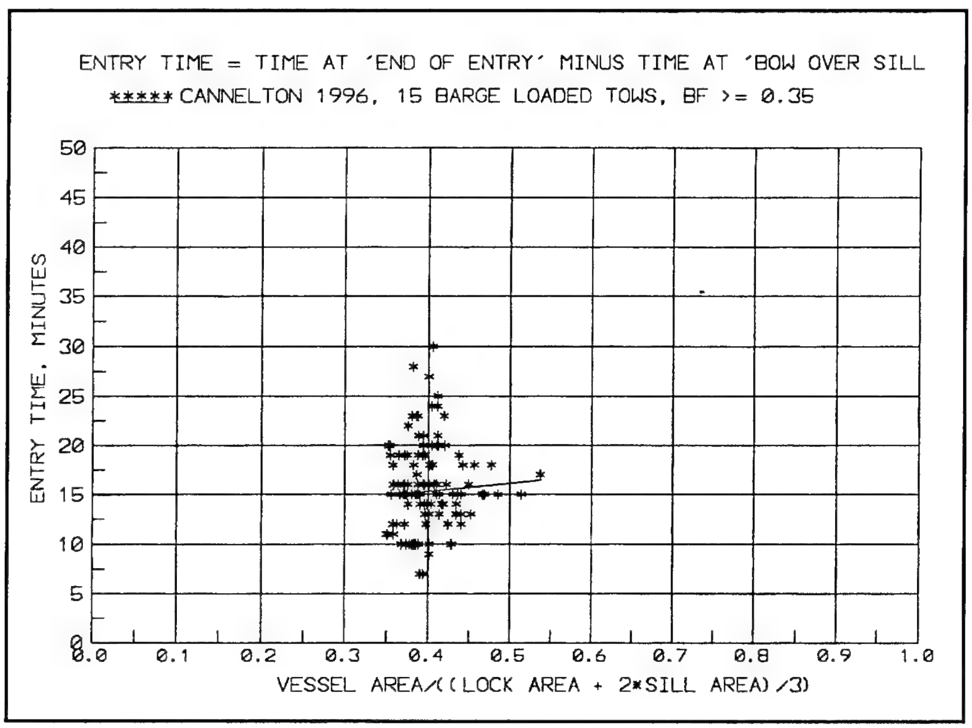

Figure 13. Entry time versus BF Cannelton Lock, 1996 (BF> 0.35)

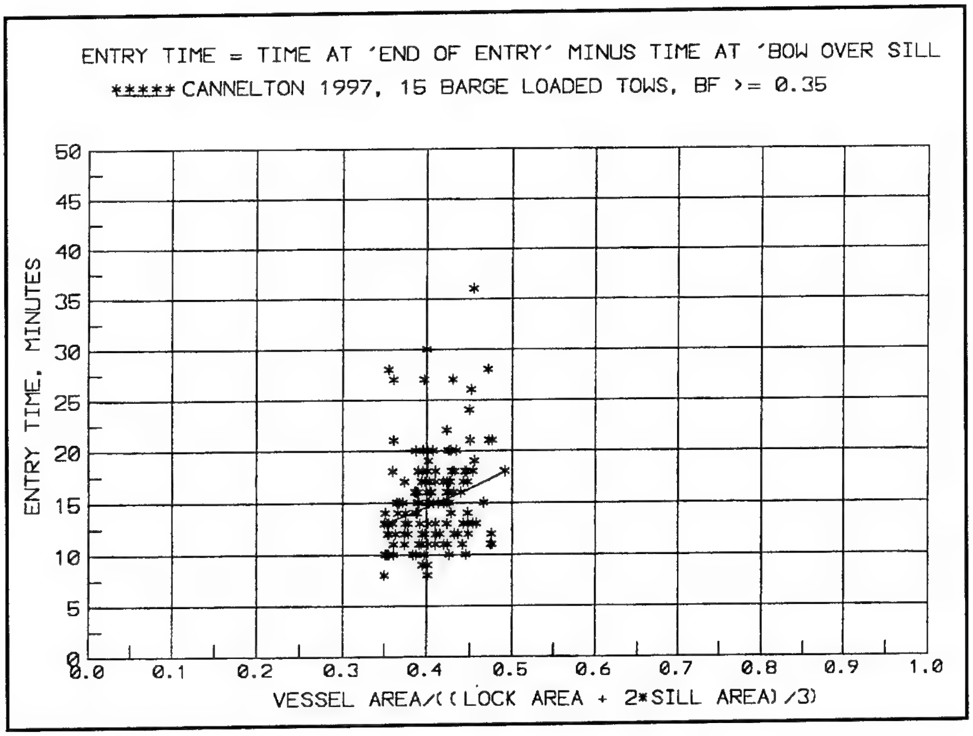

Figure 14. Entry time versus BF Cannelton Lock, 1997 (BF> 0.35)

All data (including Melvin Price and Lock 27) having BF greater than or equal to 0.35 are plotted in Figure 15 along with the best fit equation

$$T_e = 8.46 \exp (1.40 \ BF) \tag{3}$$

The data in Figure 15 has an unexplained upper limit of exactly 30 min which causes some concern. One lockman said that long entry times were reluctantly entered into the LPMS database because this was classified as some type of delay that required further action.

McAlpine versus Markland Tows

The 1997 LPMS records of upbound entering tows at McAlpine and Markland were examined to find entry times for tows going through McAlpine and then through Markland with the same tow configuration. While it would be difficult to determine if the same pilot made both lockages, this data does focus on two chambers that are identical except for sill and chamber depths. Results are plotted as the ratio of McAlpine T_e / Markland T_e versus BF at McAlpine in Figure 16 and show a clear increase in entry time at McAlpine (normal lower pool sill depth = 3.66 m (12 ft)) compared to Markland (normal lower pool sill depth = 4.57 m (15 ft)) for high BF. The best fit line is given by

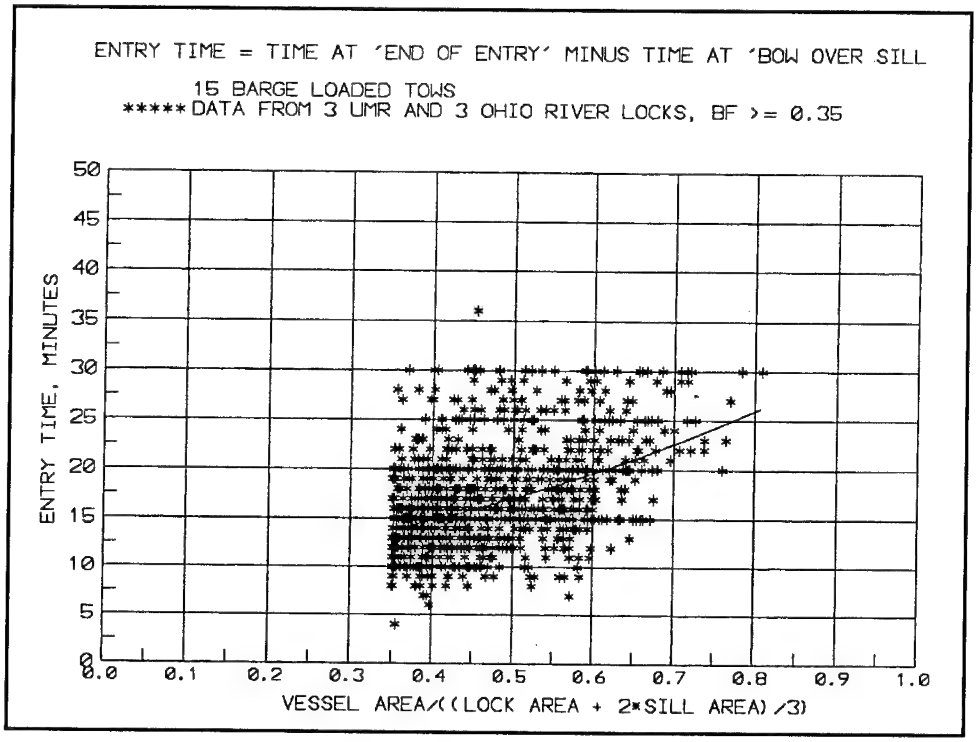

Figure 15. Entry time versus BF (All data from 3 UMR and 3 Ohio River locks having BF > 0.35)

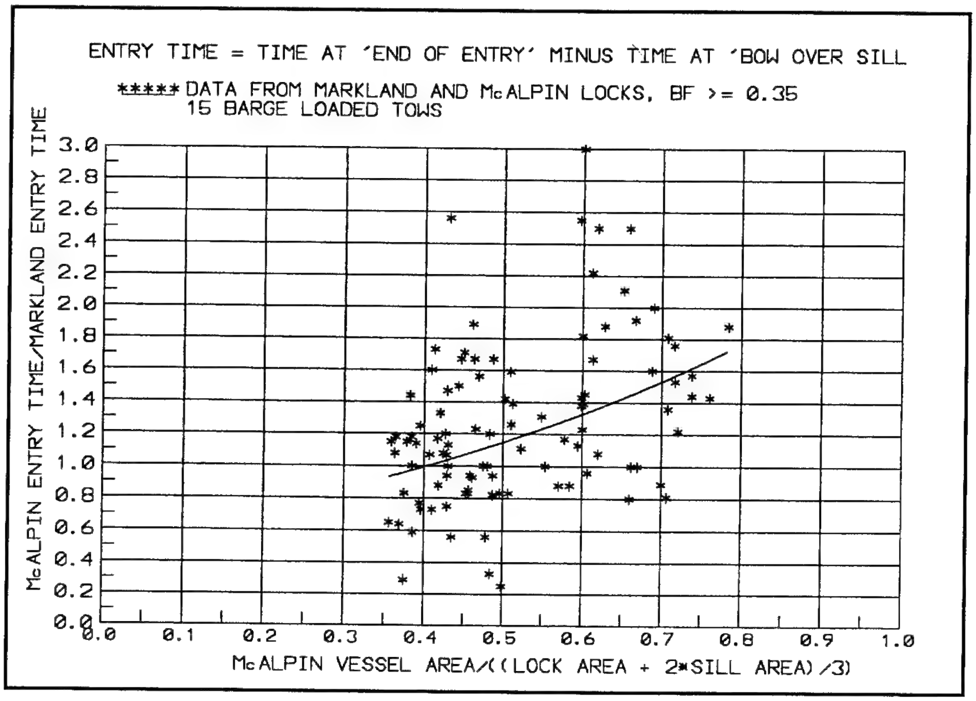

Figure 16. Ratio of entry times at McAlpin and Markland Locks versus BF at McAlpin Lock

$$\frac{\text{McAlpine } T_e}{\text{Markland } T_e} = 0.56 \exp\left[1.44 \; BF_{\text{McAlpin}}\right] \quad (4)$$

The McAlpine and Markland results also show the difference in times to be small at a BF of about 0.35.

5 Entry/Exit Times from Video Tape Data at McAlpine Lock

General Observations

The LPMS data had two serious shortcomings for the purposes of this study: (a) The database contained no information about times that could be correlated to sill effects for downbound exiting tows; and (b) the apparent limit of 30 min in the database makes the data suspect for tows having large entry times. For these reasons, cameras were installed at McAlpine Lock to obtain tow entry and exit time data. As stated previously, McAlpine is unique for 366-m locks because it has a relatively shallow lower sill depth of 3.66 m at normal lower pool elevation. The exception to this is Lock 52 which is a sheet pile cell structure untypical of most locks. One camera was installed in the upper lock approach to provide information on tow draft. It was hoped that this camera would be able to provide the actual draft of the barges on the side of the tow toward the camera and whether the other barges were loaded or unloaded. The upstream camera was only able to provide whether the barges were loaded or unloaded. The downstream camera was located downstream of the lower miter gates and directed upstream toward the lower miter gates and sill area to provide the times that gates opened or closed, the time of bow over sill, the time each barge junction passed over the sill, the time the stern of the barges passed over the sill, and the time the stern of the towboat passed over the sill. The lower camera also provided information on whether barges were loaded or unloaded. The upper and lower gauge data were obtained from the lock personnel. The Louisville District provided the LPMS data from which the draft of the tow was extracted. Entry time was determined as the difference between time at bow over sill and time at gate closure. Exit time was determined as the difference between time at the gate opening and time at the stern of towboat over the sill. Only tows having 14 or 15 barges were used in the analysis unless the tow was a chemical tow equal to a 3 by 5 tow size. Only those tows having barges that were all empty or all loaded were used in the analysis. The only exceptions to this were several tows that were classified as loaded but had one unloaded barge along with 14 loaded barges. These tows were included to increase the sample

size because the one unloaded barge was not felt to significantly alter tow entry or exit time. A second exception was one upbound unloaded tow which was a tow of eight petroleum barges having similar length and width of 15 barge tows. Data were collected between 30 September 1999 and November 19, 1999 during daylight hours only.

Entry Time for Upbound Unloaded Tows

The basic data for upbound, entering, unloaded tows from the McAlpine video tapes is shown in Table 4.

Table 4
Basic Data for Upbound, Entering, Unloaded Tows from McAlpine Video Tapes

Towboat/ Tow Number	Date	Time at Bow Over Sill	Time at Gate Closure	Entry Time min	Lower Gauge m (ft)	Number of Loaded (Empty) Barges
562268	9/30/99	17:44:59	17:58:41	13.7	329 (10.8)	0 (15)
918951	10/12/99	13:50:34	14:01:58	11.4	3.38 (11.1)	0 (8)

The few tows passing during the monitoring period prevents any conclusions from the video tape data but the upbound, unloaded data from the LPMS records were not affected by the concerns listed above. The values in Table 4 are similar to the average LPMS value of 9.1 min and well within the scatter of the LPMS data which has a standard deviation of 2.9 min.

Exit Time for Downbound Unloaded Tows

The basic data for downbound, exiting, unloaded tows from the McAlpine video tapes is shown in Table 5.

The average exit time of the eight downbound, unloaded tows was 7.6 min with a standard deviation of 0.9 min.

Entry Time for Upbound Loaded Tows

The basic data for upbound, entering, loaded tows from the McAlpine video tapes is shown in Table 6.

Table 5
Basic Data for Downbound, Exiting, Unloaded Tows from McAlpine Video Tapes

Towboat/ Tow Number	Date	Time at Gate Opening	Time at Stern of Towboat Over Sill	Entry Time, min	Lower Gauge m (ft)	Number of Loaded (Empty) Barges
575826	10/13/99	9:40:05	9:47:10	7.1	3.8 (12.4)	0(15)
575826	10/15/99	12:16:55	12:25:19	8.4	3.4 (11.1)	0(15)
575824	10/17/99	13:37:41	13:45:04	7.4	3.60 (11.8)	0(15)
575823	10/21/99	13:36:09	13:43:41	7.5	2.95 (9.7)	0(13)
562078	10/23/99	9:55:01	10:03:24	8.4	3.32 (10.9)	0(13)
577912	10/27/99	13:41:48	13:47:46	6.0	2.96 (9.7)	0(15)
?	10/29/99	17:51:37	17:58:57	7.3	3.38 (11.1)	0(13)
642652	11/10/99	13:55:22	14:04:10	8.8	3.45 (11.3)	0(15)

The LPMS data for an entering, upbound, loaded tow having a BF < 0.35 was not affected by the concerns about the LPMS data. The average entry time from the LPMS data of 13.0 min and a standard deviation of 3.9 min is considered to be valid. All tows in the above Table 6 have BF > 0.35 and represent the data needed to address the deficiencies in the LPMS data. The approach used herein is to adopt the exponential relation used throughout this report for entry time versus BF, use entry time = 13.0 min for BF = 0.35, and the Table 6 data to define the coefficients in the exponential equation. The data are plotted in Figure 17 along with the best fit equation:

$$T_e = 6.11 \exp [2.16 (BF)] \tag{5}$$

Note that Equation 5 results in T_e significantly greater than Equation 3 from the LPMS data only.

Exit Time for Downbound Loaded Tows

The basic data for downbound, exiting, loaded tows from the McAlpine video tapes is shown in Table 7. Note that tows have been included that have mixed loaded and unloaded barges. These were included because a wide range of BF is needed because, unlike the upbound, entering, loaded tow, we have no LPMS data for the downbound, exiting, loaded tow.

Table 6
Basic Data for Upbound, Entering, Loaded Tows from McAlpine Video Tapes

Towboat/ Tow Number	Date	Time at Bow over Sill	Time at Gate Closing	Entry Time Min	Lower Gauge, m (ft)	Number of Loaded (Empty) Barges	Draft, m (BF)
685578	10/2/99	15:52:12	16:21:00	28.8	2.93 (9.6)	15(0)	2.74(0.664)
569145	10/7/99	12:01:34	12:21:50	20.3	3.14 (10.3)	15(0)	2.90(0.665)
515689	10/7/99	15:30:07	15:52:17	22.2	3.14 (10.3)	15(0)	2.90(0.665)
560135	10/10/99	14:48:50	15:08:53	20.1	3.60 (11.8)	15(0)	2.74(0.568)
575826	10/10/99	15:56:37	16:21:05	24.5	3.60 (11.8)	15(0)	2.90(0.599)
296549	10/12/99	16:10:36	16:34:26	23.8	3.51 (11.5)	15(0)	2.74(0.579)
644959	10/13/99	13:40:56	14:10:50	29.9	3.45 (11.3)	15(0)	2.84(0.609)
562268	10/17/99	11:12:42	11:40:11	27.5	3.54 (11.6)	15(0)	2.90(0.607)
514563	10/17/99	17:07:19	17:20:58	13.7	3.63 (11.9)	14(1)	2.90(0.595)
579562	10/18/99	11:55:10	12:38:55	43.8	2.90 (9.5)	14(0)	3.20(0.781)
579878	10/21/99	10:04:35	10:25:00	20.4	2.96 (9.7)	15(0)	2.95(0.708)
641346	10/22/99	11:35:52	11:57:35	21.7	3.14 (10.3)	15(0)	2.90(0.665)
240135	10/23/99	17:57:01	18:26:22	29.4	2.93 (10.2)	15(0)	2.84(0.658)
646853	10/24/99	8:32:21	8:57:16	24.9	2.93 (9.6)	15(0)	3.05(0.738)
616800	10/24/99	13:00:15	13:24:19	24.1	2.96 (9.7)	15(0)	2.90(0.696)
664991	10/26/99	9:13:39	9:42:01	28.4	3.05 (10.0)	14(1)	2.74(0.644)
641346	10/30/99	9:10:18	9:37:53	27.6	3.11 (10.2)	15(0)	3.05(0.705)
500419	10/30/99	13:42:04	14:16:02	34.0	3.05 (10.0)	15(0)	2.90(0.680)
520785	11/10/99	15:03:54	15:24:35	20.7	3.38 (11.1)	15(0)	2.90(0.628)
1044132	11/11/99	10:56:26	11:15:14	18.8	3.32 (10.9)	15(0)	2.90(0.637)
240135	11/11/99	12:04:05	12:30:34	26.5	3.29 (10.8)	14(0)	2.90(0.642)
584932	11/12/99	14:05:35	14:30:41	25.1	3.32 (10.9)	15(0)	2.74(0.604)

Note: Times after change from daylight-saving time (10/31/99) are one hour later than actual.

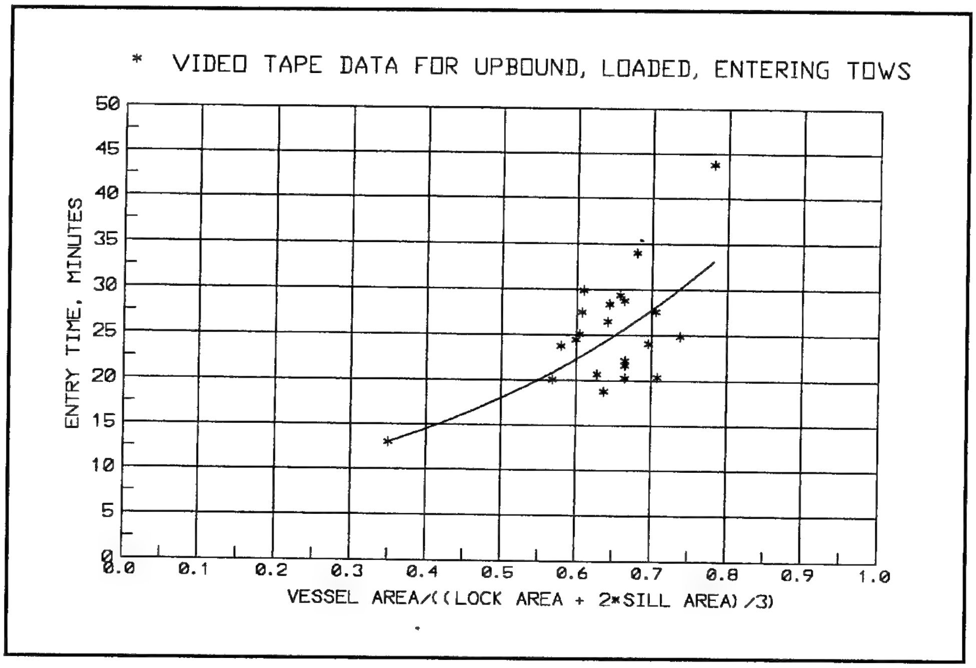

Figure 17. Entry time versus BF (video tape data from McAlpin Lock)

The Table 7 data are shown in Figure 18 for data having BF > 0.35 along with the best fit curve for downbound, exiting, loaded tows

$$T_e = 5.90 \exp [1.51 (BF)] \tag{6}$$

Based on the limited data available in Table 7 and the projection of equation 6 to BF = 0.35, downbound, exiting, loaded tows having a BF < 0.35 have an exit time of 11 min. Equation 6 for downbound, exiting, loaded tows having a BF > 0.35 has a much flatter curve and lower values than Equation 5 for upbound, entering, loaded tows indicating lesser sill effects for the downbound, exiting, loaded tow.

Summary of Times for Entry and Exit

Based on the data from the LPMS database and the cameras at McAlpine Lock, the entry and exit times in Table 8 are recommended:

As shown in Table 8, Equations 5 and 6 can be used with drafts greater than 2.74 m (9 ft) to address overloaded tows, but both equations should be limited to BF of about 0.75.

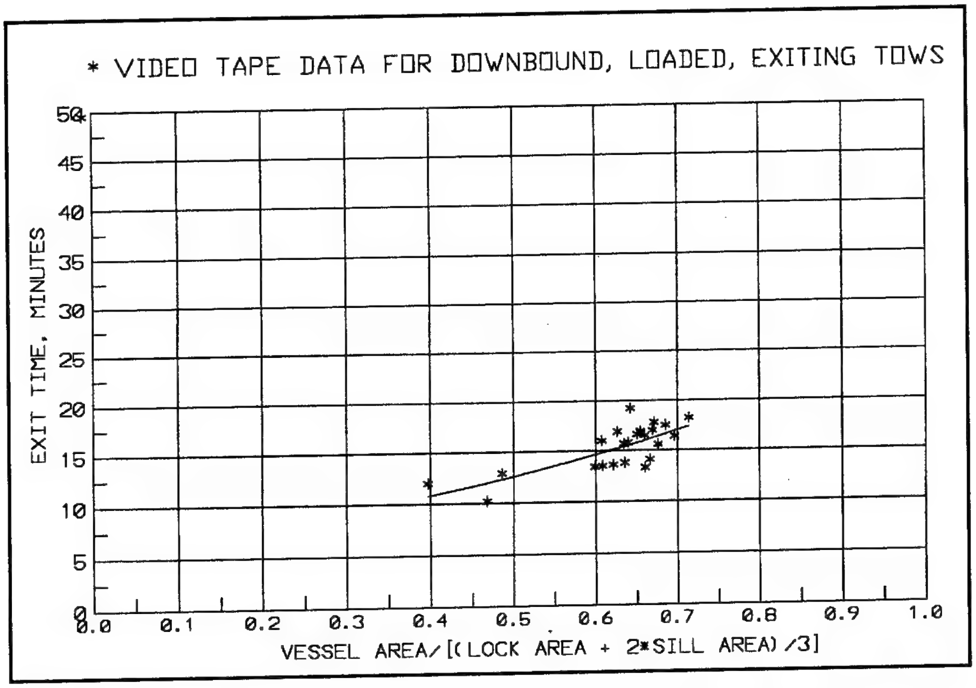

Figure 18. Exit time versus BF (video tape data from McAlpin Lock)

Table 7
Basic Data for Downbound, Exiting, Loaded Tows from McAlpine Video Tapes

Towboat/ Tow Number	Date	Time at Gate Opening	Time at Stern of Towboat over Sill	Entry Time Min	Lower Gauge m (ft)	Number of Loaded (Empty) Barges	Draft, m (BF)
279623	9/30/99	11:26:36	11:37:33	11.0	3.32 (10.9)	5(3)	2.90(0.237)
520785	9/30/99	13:10:42	13:23:38	12.9	3.29 (10.8)	12(0)	2.74(0.486)
275810	9/30/99	14:10:15	14:29:28	19.2	3.29 (10.8)	15(0)	2.90(0.642)
560135	10/1/99	15:38:27	15:51:58	13.5	3.29 (10.8)	14(2)	2.74(0.608)
552894	10/2/99	10:02:30	10:16:18	13.8	3.11 (10.2)	14(1)	2.74(0.635)
293607	10/2/99	13:06:33	13:24:45	18.2	2.99 (9.8)	14(0)	3.00(0.714)
916834	10/3/99	10:43:26	10:59:08	15.7	3.17 (10.4)	8(0)	2.74(0.634)
579562	10/4/99	10:04:18	10:18:25	14.1	3.35 (11.0)	15(1)	3.05(0.666)
614765	10/5/99	8:37:30	8:55:02	17.5	3.02 (9.9)	15(0)	2.90(0.685)
578276	10/9/99	11:00:43	11:18:32	17.8	3.14 (10.3)	14(1)	2.92(0.671)
515689	10/09/99	12:17:30	12:30:46	13.3	3.17 (10.4)	14(1)	2.90(0.660)
288062	10/09/99	13:28:25	13:42:03	13.6	3.20 (10.5)	14(2)	2.74(0.621)
290088	10/13/99	15:28:55	15:40:55	12.0	3.29 (10.8)	8(2)	2.90(0.397)
562268	10/13/99	16:38:04	16:54:01	16.0	3.23 (10.6)	13(0)	2.90(0.607)
264863	10/14/99	10:22:24	10:38:48	16.4	2.96 (9.7)	15(0)	2.90(0.696)
567944	10/14/99	17:27:46	17:43:34	15.8	3.14 (10.3)	12(3)	2.92(0.639)
641346	10/16/99	9:11:05	9:26:40	15.6	3.11 (10.2)	15(0)	2.92(0.676)
562018	10/16/99	18:08:02	18:25:02	17.0	2.90 (9.5)	15(0)	2.74(0.669)
610971	10/21/99	15:56:06	16:06:45	10.7	2.96 (9.7)	3(12)	2.82(0.219)
500419	10/22/99	13:25:38	13:42:31	16.9	3.17 (10.4)	15(0)	2.74(0.626)
560135	10/23/99	11:25:08	11:35:18	10.2	3.29 (10.8)	10(3)	2.92(0.468)
614765	10/24/99	11:40:56	11:57:50	16.9	2.99 (9.8)	14(0)	2.74(0.654)
641346	10/27/99	15:37:09	15:53:41	16.5	2.96 (9.7)	15(0)	2.74(0.659)
584006	10/28/99	16:52:35	17:05:58	13.4	3.35 (11.0)	15(0)	2.74(0.599)
572403	11/15/99	10:24:00	10:40:33	16.6	3.20 (10.5)	15(0)	2.87(0.650)

Note: Times after change from daylight-saving time (10/31/99) are one hour later than actual.

Table 8
Computed Entry and Exit Times for Selected Tows and Sill Depths at a Lock Having a 0.3048-m- (1-ft-) High Sill and 3-Barge-Wide by 5 Barge-Long Tow

Draft of Barges m (ft)	Sill Depth m (ft)	Chamber Depth, m (ft)	BF	Exit Time Min	Entry Time Min
0.61 (2)	> 3.66 (12)	> 3.96 (13)	< 0.15	7.6	9.1
2.74 (9)	> 7.32 (24)	> 7.62 (25)	< 0.35	11.0	13.0
2.74 (9)	5.49 (18)	5.79 (19)	0.469	12.0	16.8
2.74 (9)	4.57 (15)	4.88 (16)	0.560	13.7	20.5
2.9 (9.5)	4.57 (15)	4.88 (16)	0.591	14.4	21.9
3.05 (10)	4.57 (15)	4.88 (16)	0.622	15.1	23.4
2.74 (9)	3.66 (12)	3.96 (13)	0.697	16.9	27.5

6 Discussion of Results and Conclusions

In the design of locks, sill and chamber depths affect (a) the ability of tows to enter/exit the lock, (b) the safety of entry and exit, (c) delays related to ice, and (d) the required entry/exit time.

Ability of Tows to Enter/Exit Lock

To insure that tows will be able to enter or exit a lock at any anticipated stage, consideration must be given to historical minimum tailwater or anticipated future minimum tailwater to insure that the condition will not arise that the tow cannot enter/exit the lock.

Safety

Safe passage over the sill is required to prevent tows from causing damage to the sill, upper miter gates, or to the tow. While the Rivers and Harbors Act of 1917 states that at least 0.08 m (3 in.) of clearance must be maintained between the sill and vessel bottom, larger clearances are warranted based on experience at Locks and Dam 52 and from physical model experiments of Locks and Dam 52. The largest squat of the model tow was 0.5 m (1.6 ft) using a thrust of less than the maximum thrust. The Locks and Dam 52 prototype lower sill has a minimum depth of 3.35 m (11 ft) and has been damaged by tows having an unknown draft which on the Ohio is frequently greater than 2.74 m (9 ft). Lock 15 on the UMR has a 3.35-m (11 ft) lower sill depth and has no reports of vessels striking the lower sill. Based on these model and prototype experiences, clearance beneath the design vessel should be 0.61-0.91 m (2-3 ft) to prevent the tow from striking the sill.

Delays Related to Ice

In the presence of ice accumulation on the bottom of barges, significant delays have resulted when sill depths are low. Projects experiencing ice delays are not those in the coldest climates because rapid freeze-up stops navigation. Projects such as Locks 19 to Melvin Price on the UMR experience ice related delays that include accumulation of ice on the bottom of the barges. Under extreme conditions, accumulations of ice have reached 2.44 m-3.05 m (8-10 ft) in thickness beneath the barges at old Lock 26. For upper or lower sill depths of 4.57 m (15 ft) or less, tows on these UMR locks report significant problems getting the barges across the sill. These problems were estimated to occur every 3-5 years for only a small portion of the navigation season. Sill depths of 5.8 m (19 ft) and greater did not experience significant delays related to ice accumulation on the barges. Chamber depths must also be considered because UMR locks report problems with tows breaking wires when tows are lowered and sit down on top of the accumulated ice. The Illinois Waterway reported few problems with ice accumulation, possibly due to the shallow channel depths. The Ohio River locks reported few problems with ice accumulation on the barge bottom. Significant fleeting of barges on the UMR, as compared to lesser fleeting activities on the Ohio River, may lead to greater ice accumulation. Almost all locks report the need for ice lockages or passage of ice through adjacent auxiliary chambers.

Required Entry/Exit Time

The primary issue in establishing sill and chamber depths is the cost of reduced project benefits for excessive entry/exit time. While any 2.74-m- (9-ft-) draft by 32-m- (105-ft-) beam tow can pass safely over a 3.66-m- (12-ft-) sill depth in a 33.5-m (110-ft-) wide lock, the entry/exit time may not be satisfactory for present or future traffic levels. A BF is defined which is an alternative to the commonly used ratio sill depth/draft and represents both depth and draft and beam and width of the tow and the lock. Whether from the LPMS or video tape data presented herein, the data exhibit considerable scatter for the same BF due to various environmental, human, and navigation factors that have little to do with sill and chamber depths. Some tows push in or out of a lock with a large propeller thrust while some are content to accept slower entry/exit using less thrust.

Based on experiments in the physical model of Lock 52 on the Ohio River, upbound entry and downbound exit times will decrease if emptying valves are left open.

Based on observed data at six locks, upbound unloaded 15 barge tows will enter in an average time of 9.1 min, based on data having sill depth $\geq$4.0 m (13 ft). Entry time is defined as the difference in time between the bow over the sill and the closure of the downstream miter gates. Fifteen loaded barge tows in

large lock depths (BF < 0.35) will enter in an average of 13 min. Only 15 barge tows in locks having sill depths of about 7.3 m (24 ft) or less have entry times that are affected by the depth in the chamber and over the sill. Equation 5, based on McAlpine video tape data, defines entry times for upbound loaded tows having BF > 0.35.

Based on observed video tape data at McAlpine Lock, downbound unloaded 15 barge tows will exit in an average time of 7.6 min. Exit time is the difference between time at the gate opening and passage of the towboat stern over the lower sill. Fifteen loaded barge tows in large lock depths (BF < 0.35) will exit in an average of 11 min. Only 15 barge tows in locks having sill depths of about 7.3 m (24 ft) or less have exit times that are affected by the depth in the chamber and over the sill. The sill effects on the downbound, loaded tow are much less than on the upbound loaded tow. Equation 6 defines exit times for downbound loaded tows having BF > 0.35.

If a 2.74-m- (9-ft-) draft by 32-m- (105-ft-) beam tow were to use the same propeller thrust in a 3.66-m (12-ft) sill depth that is used in a 4.57-m (15-ft) sill depth lock, the difference in entry times for the two depths would be larger than the difference based on using the curve in Figure 17. The data suggest that the typical tow is exerting a larger propeller thrust in the smaller sill depth than in the larger sill depth. This tendency of the pilot to increase thrust as a response to a slow entry or exit speed means that deeper sill depths do not decrease entry times as much as they would if one did not account for these other environmental, human, and navigation factors and used results such as Kooman's experiments for a constant propeller speed for any depth. Physical model studies of entry/exit times are of limited value because they do not account for the overriding and highly variable influence of these other factors. Other factors also limit entry times for loaded tows to about 13 min in locks that are so deep that the lock size has no physical effect on the speed.

For mixed tows having both loaded and unloaded barges, the following is recommended:

a. For tows having three loaded barges abreast plus other barges, the number of loaded and unloaded barges should be used to interpolate between the results of Equation 5 and the minimum time for fully loaded tows of 13 min (upbound entering) and equation 6 and 11 min (downbound exiting). (The basis for using time for a loaded tow in deep water as the beginning point for the interpolation rather than the time for unloaded barges is that tows with some loaded barges will have a minimum entry time closer to that of a loaded tow in deep water rather than an unloaded tow). For example, an upbound entering 3 by 5 tow having 6 loads (2 by 3) and 9 empties (3 by 3) entering McAlpine lock with a 2.74-m (9-ft) draft and a 4.57-m (15-ft) sill depth will have an approximate entry speed of (6/15)(20.5-13) + 13 = 16.0 minutes.

b. For tows having no portion that is 3 wide abreast, compute BF for the tow and use either 13 min if BF < 0.35 or results from Equation 5 or 6 for

BF > 0.35. For example, an downbound exiting 3 by 5 tow having 10 loads on one side and 5 empties (draft = 0.61 m) on the other side at McAlpine lock with a 3.66-m- (12-ft-) sill depth will have BF = (2x9x35+2x35)/ 1356.7 = 0.516 and entry time from Equation 6 = 12.9 min.

In summary, this study provides entry and exit times for a range of sill depths and tow configurations. These times can be used to compare costs of lockage delays to the cost of building deeper locks.

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14. ABSTRACT

In the design of locks, sill, and chamber depths affect (a) the ability of tows to enter/exit the lock, (b) the safety of entry/exit, (c) delays related to ice, and (d) the required entry/exit time. The primary issue in establishing sill and chamber depths is the cost of reduced project benefits for excessive entry/exit time. This study provides entry and exit times for a range of sill depths and tow configurations.

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